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THESIS

SEMICONDUCTOR LASER DIODES AND THE DESIGN OF A D.C. POWERED LASER DIODE DRIVE UNIT

by

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June 1988

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Semiconductor Laser Diodes and the Design of a D.C. Powered Laser Diode Drive Unit

by

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Submitted in partial fulfillment of the
requirements for the degree of

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ABSTRACT

This thesis addresses the design, development and operational analysis of a D.C. powered semiconductor laser diode drive unit. A laser diode requires an extremely stable power supply since a picosecond spike of current or power supply switching transient could result in permanent damage. The design offers stability and various features for operational protection of the laser diode. The ability to intensity modulate (analog) and pulse modulate (digital) the laser diode output for data transmission was a major design consideration. Laser optical power is controlled via a closed loop system using a monitor photodiode. Laser diode temperature stabilization is accomplished with the use of a thermoelectric cooler. Laboratory and remote applications were considered in the design of this unit.

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I would like to take this opportunity to thank Professor John P. Powers for the inspiration to proceed into the study of electro-optics. His enthusiastic approach to the subject greatly influenced my studies here at the Naval Postgraduate School. I would also like to acknowledge and thank Mr. John Glenn, the electro-optics lab manager, for his invaluable assistance throughout my work on this thesis. Last, but certainly not least, I would like to thank my wife, Alison, for her love, and her support of my work during the past two and one-half years at the Naval Postgraduate School.

I. INTRODUCTION

A. PURPOSE OF THESIS/BACKGROUND INFORMATION

This thesis is a subset of ongoing research projects at the Naval Postgraduate School which involve the design and development of a long haul, underwater fiber-optic communications link. The particular aspect addressed involved the design, development, and operational analysis of a D.C. powered, semiconductor laser drive unit. Of primary importance in the design is the requirement for low power consumption and high reliability to support long-life remote operation without battery replacement. Other desired features incorporated into the design are discussed throughout this report.

Continuous wave semiconductor laser diodes are advanced devices in which the light excited by the drive current is confined to a very narrow region of the semiconductor crystal. This creates a highly directional and coherent light source which is very nearly monochromatic. Since these devices operate at extremely high internal field strengths, a picosecond spike of current or power supply switching transient could turn the laser into a side emmiting LED or, worse yet, burn it up altogether. For this reason, continuous wave semiconductor lasers require an extremely stable power supply.

B. DRIVE UNIT REQUIREMENTS/DESIRED SPECIFICATIONS

The desired specifications and capabilities are that the unit be able to drive a wide variety of semiconductor lasers and also be capable of analog modulation rates of approximately 300 MHz or greater. Output control of the laser is via current control or optical power control (with the use of a monitor photodiode). Current limiting protective circuitry for the laser diode is also a highly desirable feature. Temperature stabilization of the laser is accomplished by the use of a thermoelectric cooler. Each of these specifications and features will be discussed in much greater detail throughout this paper.

The Control and Display aspect of this project is an integral part of this unit. The display unit centers around a digital multimeter. The DMM readout is switchable to the various parameters controlled by the laser drive unit. These parameters consist of current limit, thermoelectric cooler setpoint temperature, laser bias level, laser drive current, and optical power.

C. PROJECT OVERVIEW

The next chapter discusses semiconductor laser diode characteristics and desired performance for use in optical broadband transmission systems. Then, the manufacture and architecture of the laser diode and considerations involving source wavelength is discussed. A brief discussion of laser diode reliability is brought up primarily as background information for use in driver circuit design considerations. The laser diode being utilized in this research is described with emphasis on features particular to that laser diode. One of the major features of the LASERTRON laser diode is the incorporation of a thermoelectric (TE) cooler into the 14 pin DIP. Because of the great importance of maintaining relatively low and steady temperatures of laser diodes, and the incorporation of the TE cooler directly onto this chip, an in-depth review of the theory, manufacture, and implementation of thermoelectric coolers and the Peltier effect is undertaken. Turning to modulation and encoding of optical signals using laser diodes as a source, various modulation techniques are discussed and considerations made for implementation in the laser drive circuit design. It is hoped that at the conclusion of chapter two, the reader will possess a basic background and understanding of semiconductor lasers and drive requirements for implementation in a long haul communications link.

Chapter Three is the heart of this research and design work. It is here that ideas and characteristics reviewed in chapter two are finalized and implemented in the drive unit. A basic description and block diagram of the layout and operation of this project begins this chapter. A description of each section of the unit beginning with the power supply is given. Power supply requirements (i.e., required voltages, total load, etc.) are reviewed and a circuit design capable of supporting the required specifications of the unit is presented. Following this is a description of the Control and Display circuit. This part of the unit displays control parameters such as current limit and laser bias point, and is also used to display a digital readout of drive current, optical power, and temperature of the laser. An examination of the laser driver circuitry and modulation circuitry with a complete description and operational analysis concludes this chapter. Schematic diagrams of each sub-unit mentioned above are included in chapter three.

Chapter Four describes various operational procedures and unit setup. This includes a description of recommended parameters for initial startup and unit performance analysis procedures. This chapter also includes an interesting section on wavelength tuning of the laser via laser operating temperature control utilizing the thermoelectric cooler.

Chapter Five discusses the varied applications of this D.C. powered laser drive unit. The chapter highlights the flexibility of the design for use not only in a laboratory environment, but also in remote applications such as underwater fiber-optic transmission systems. A discussion of possible configuration changes that may need to be implemented to adapt to different applications is undertaken.

Chapter Six summarizes the research and design effort and reiterates the goals of the thesis and the net results. This section also looks into possible improvements to the design or follow on work in order to enhance performance and/or improve on ancilliary features. Considerations for adaptation to very wideband (DC - several GHz) transmission systems will be discussed.

II. SEMICONDUCTOR LASER DIODES

A. BACKGROUND AND CHARACTERISTICS

Semiconductor laser diodes are primarily utilized as source transmitters in optical broadband transmission systems. Their small size, relatively high level of efficiency, narrow spectral width, and high modulation rate capacity provides superior performance characteristics relative to other light sources (mainly LED's). Optical coupling into fibers is also superior. The primary requirements for the employment of semiconductor laser diodes in a broadband transmission system can be summarized as follows [Ref.1:p.22]:

1. Modulation capacity of several GHz
2. Overall power consumption should be low (i.e., low threshold current, low forward voltage, high efficiency)
3. Low intensity noise
4. Laser diode should exhibit single mode (SM) characteristics
5. Little sensitivity to optical feedback in the laser
6. Far field pattern should allow high coupling efficiency into SM fiber

B. PROPERTIES/MANUFACTURE OF SEMICONDUCTOR LASERS

Semiconductor III-V compounds GaAlAs and InGaAsP are used to manufacture semiconductor lasers. The emission wavelength of GaAlAs is approximately 0.8 to 0.92 um, while

InGaAsP emits at wavelengths ranging from 0.92 um to 1.65 um, depending on material thickness, composition and doping levels. The emission wavelength is determined by the band-gap energy (E_g), in eV, of the recombination region of the semiconductor material. This wavelength (in um) can be determined from the following equation [Ref. 2:p. 11]:

$$\lambda = 1.2/E_g \qquad (2\text{-}1)$$

The material parameters can also be adjusted to either obtain optimal peak optical power output in pulsed operation, or to reduce threshold current to a minimum required for CW laser operation. In this paper, the primary concern will be CW laser operation.

The semiconductor compounds mentioned above are grown epitaxally on a GaAs or InP substrate. This produces multi-layer structures, with each layer differing in composition. The transition between layers is referred to as a heterojunction. Figure 2.1 shows the basic structure of a semiconductor laser of typical dimensions [Ref. 1:p. 23]. The ability to manufacture these heterostructures allows current densities at reduced levels to permit continuous operation of the laser diode. The layers are set up to allow light to make the equivalent of several passes through a low gain active region (optically amplifying) between n and p type confinement layers. This forms an optical resonator with parallel front and rear surfaces acting as reflectors which are formed by the cleaved facets of the crystal. This structure forms a Fabry-Perot resonator.

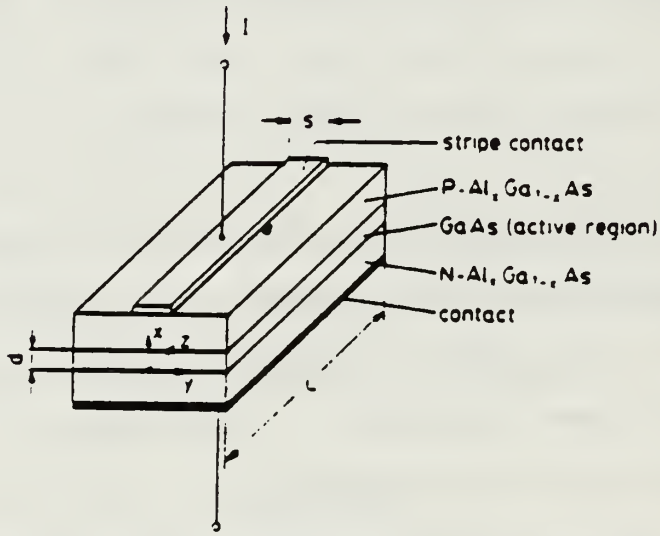

Figure 2.1. Basic Semiconductor Laser Structure (from Ref. 1)

The easiest method of confinement is to make the electrical contact on the crystal as narrow as possible (several um). This then injects charge carriers into the active region over a narrow stripe. This produces a gain profile in which light is amplified inside the center region and absorbed outside the region. This method of manufacture produces what is known as a Gain-Guided laser. A major drawback of this process is that it results in high threshold currents of 80-300 mA [Ref. 1:p. 23], primarily due to the optical absorption losses in the external region (i.e., in the region without gain). In general, the output of a gain-guided laser will consist of several frequencies centered on a nominal frequency as shown in figure 2.2. The frequency spacing $\Delta\nu$ is determined by the spacing of the front and rear reflective surfaces (L), and is given by [Ref. 3:p. 117]:

$$\Delta\nu = c / 2L \qquad (2\text{-}2)$$

where $\Delta\nu$ is the frequency spacing and c is the speed of light (vacuum).

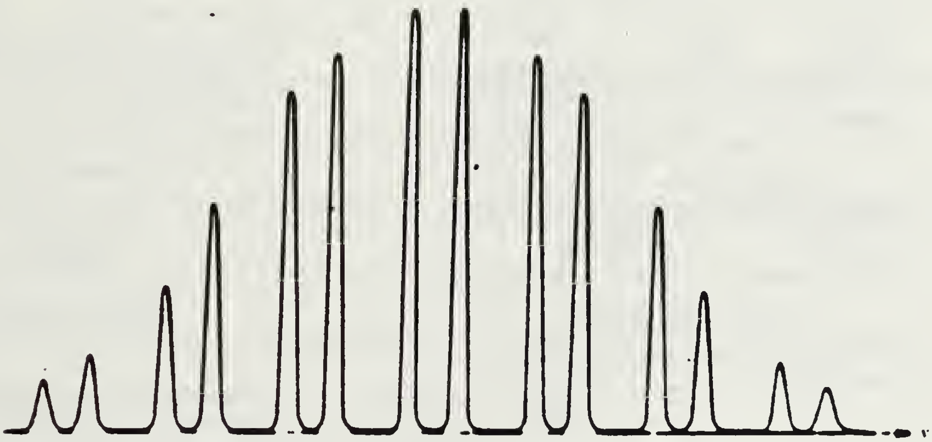

Figure 2.2. Typical Spectral Output of a Semiconductor Diode (from Ref. 3)

In a slightly altered structure, the active region is surrounded by material with a lower refractive index. The charge carriers are guided transversally by means of potential barriers. Due to a high concentration of current inside the active region, combined with effective index guidance of the light, this design permits much lower threshold currents (10 - 20 mA) [Ref. 1:p. 24]. This type of laser is referred to as a Buried Heterostructure (BH) Laser. Figure 2.3 shows a detailed structure of both the gain guided and BH lasers. A LASERTRON QLM-1300-SM-BH laser was employed for all testing of the drive unit designed in this research. A complete description (along with specifications) of the Lasertron laser diode is included in Chapter Three.

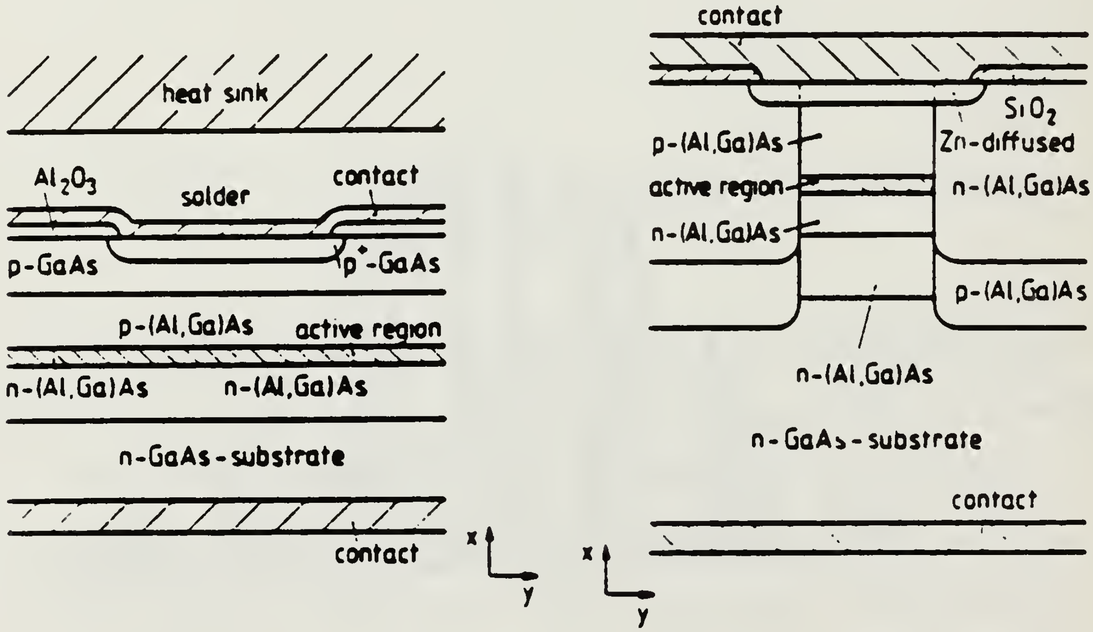

Figure 2.3. Detailed Structure of a) Gain Guided and b) Buried Heterostructure lasers (from Ref. 1)

A laser diode is characterized by a threshold current, I_{TH}, below which lasing does not occur. Above I_{TH} the carrier lifetime is very short (this allows high modulation rates via low rise times), emission spectra is on the order of a few nanometers, and the external quantum efficiency becomes relatively high. The power-current curve of laser diodes, however, frequently exhibit slope changes known as kinks. The origin of these kinks could possibly be defects in the junction region, producing lasing in filaments. Another cause of the non-linearity could be the result of lateral mode changes in the laser. Narrow planar stripe lasers normally operate in a single lateral mode near threshold. As a result of increasing current to near saturation, more modes may appear. The power output in the fundamental mode tends to saturate and the second mode then becomes dominant. The major problem resulting from the non-linearities in the power-current curve is that of harmonic distortion and intermodulation of multiple signals carried on an analog communications system link. From this discussion it is obvious that operation of the laser diode in a linear region is critical to effective and efficient performance of an optical communications link.

C. SOURCE WAVELENGTH CONSIDERATIONS

Since a primary employment of semiconductor lasers is in fiber-optic communications links, it is highly desirable to optimize the performance of all elements of the fiber-optic system, including the optical fiber. The range of wavelengths output from InGaAsP lasers is between 0.92 um and 1.65 um as discussed earlier. This is a particularly suitable range as can be seen from figure 2.4(a) and 2.4(b). Figure 2.4(a) is an aggregate plot of the attenuation of light in a single mode fiber (silica) as a function of wavelength. This attenuation occurs due to the scattering and absorption of light. The scattering losses can be attributed to density variations in the fiber with a periodicity less than the wavelength of the light resulting in the curve labeled **Rayleigh Scattering** (predominant at shorter wavelengths). Optical absorption losses arise from the impurities in the fiber (i.e., copper, iron, nickel, chromium, and hydroxl ions) and the basic fiber material itself. These absorption losses, therefore, provide a minimum attainable loss for any specific fiber material and as can be seen, occur primarily at the UV and IR wavelengths.

Figure 2.4(b) shows various dispersion curves as a function of wavelength. Curve A represents the fiber material dispersion, curve B the waveguide dispersion and curve C the total chromatic dispersion. It can be seen that the sum of the material and waveguide dispersion curves yield curve C which has a zero crossing at approximately 1.3um. This represents the wavelength at which total dispersion (in ps/km-nm) is zero. This results in maximum data rate capability and fiber bandwidth utilization. As can be determined from these graphs of fiber loss and fiber dispersion, the lowest attenuation occurs at wavelengths of approximately 1.55 um (0.2 - 0.3 dB/km) while the zero dispersion wavelength is in the area of 1.3 um (0.4 - 0.5 dB/km). Therefore, the system designer must make a tradeoff as to what measure of performance must be optimized. If low losses over long distances is the primary concern, then a source wavelength of 1.55 um would be utilized. If maximum utilization of channel (fiber) bandwidth is of primary importance, then a source wavelength of 1.3 um would be employed in the system. Recent advances in fiber technology, however, have allowed control of the zero dispersion wavelength of a type of fiber known as dispersion shifted fiber. The zero dispersion point can be shifted to higher wavelengths (namely 1.55 um) by appropriate levels of doping of the silica material with germanium. The use of these fibers then allows high data rate transmission over long distances at a source wavelength of 1.55 um.

Cost is not of major concern when considering a source between 1.3 um and 1.55 um. Both lasers fall into the long wavelength category (>1 um) and the significant jump in cost from short wavelength (<1 um) to long wavelength has already occurred. Of course there is a large difference in cost between LED's and lasers (as much as one order of magnitude). For long distance, high data rate systems, long wavelength sources are a must for competitive performance.

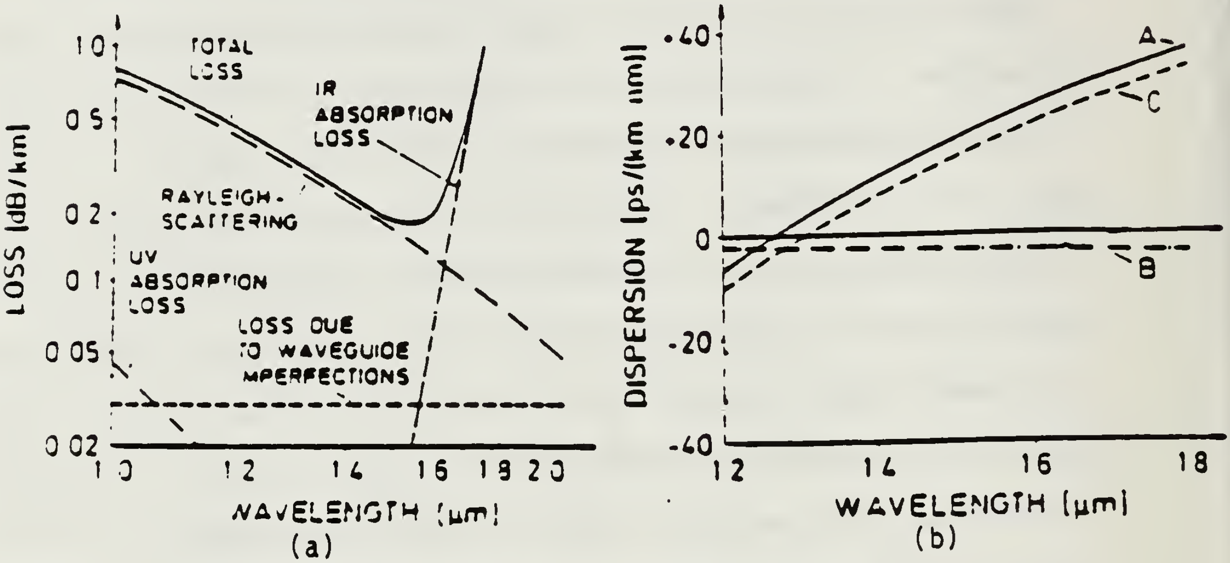

Figure 2.4. Silica Fiber a) Loss Curves b) Dispersion Curves (from Ref. 1)

D. SEMICONDUCTOR LASER RELIABILITY

Semiconductor laser reliability is of a primary concern as a system is only as reliable as its weakest element. In this section, we will briefly examine laser diode reliability and the various sources and mechanisms of laser degradation. We will then discuss various methods in which to improve laser lifetimes and operating efficiency, including drive circuit design, operation, and handling.

Laser life is limited by catastrophic damage (facet damage) or gradual degradation. The first consists of damage to the mirror caused by excessive optical flux density, and the second is a function of current density (electron-hole recombination rate), operating duty cycle and laser fabrication defects. Laser structure and type of material used are also important factors in laser reliability. [Ref. 2:p. 52]

Operationally, laser failure occurs as a result of transient pulses (which may exceed 10 x I_{TH}) found in turning power supplies on and off. These transients could result in mechanical damage to the facet. The actual damage threshold will vary among lasers and is dependent on structural flaws that may exist at the laser facet (crystal defects such as dislocations and impurities). These flaws tend to initiate damage to the laser at much lower levels of optical flux density. Methods to increase the damage threshold by depositing anti-reflective films (SiO_2 or Al_2O_3) on the laser facet have proven very successful. The effect of this film deposition is to lower the ratio between the optical flux density inside and outside the crystal. The one problem with this method is that the lowered reflectivity also increases I_{TH}. Approximate predictions of facet damage levels of optical flux can be determined from the following equation [Ref. 2:p. 53]:

$$\frac{P'_c}{P_c} = n \frac{(1-R)}{(1+R^{1/2})^2} \qquad (2-3)$$

where

P'_C/P_C = Ratio of critical power levels with and without film deposition.

n = Refractive index of GaAs (approximately 3.6)

R = Facet reflectivity.

Facet damage is generally initiated in the center of the active region under the stripe contact. In this region, optical flux densities are at a maximum.

A milder form of facet damage (erosion) will appear over the diode operating life. A typical laser diode will exhibit an exponential decrease in output power over its lifetime. The reasons for this decrease are many, only a few of which will be discussed here. The gradual degradation of the laser facet is characterized operationally by a decrease in differential quantum efficiency of the laser and in increase in threshold current I_{TH}. It has been found that facet erosion is much larger in AlGaAs lasers than in InGaAsP lasers due to the high affinity of aluminum for oxygen. Defects introduced into the recombination region during diode fabrication tend to become non-radiative recombination centers resulting in a reduced quantum efficiency. The degradation of the laser occurs in stages. In the early stages, when the density of non-radiative recombination regions is low, spontaneous efficiency decreases with only minor effects on lasing properties. As operation time increases, dark lines appear in the near field emission pattern of the degraded laser resulting in a rapid fall-off in the output of the CW laser at room temperature.

With an increase in temperature, defect propagation occurs at an accelerated rate. Therefore, the gradual degradation of the laser is accelerated, resulting in a shorter time to failure. It can be shown that the laser degradation rate increases with temperature following an expression of the form exp(E/KT), where E is the activation energy (empirically determined), K is Boltzmann's constant (1.38 x 10^{-23} J/K) and T is the operating temperature of the laser [Ref. 3:p.130]. Figure 2.5 shows the time required for a 20% increase in threshold current as a function of ambient temperature. This data was taken from a group of Al_2O_3 facet coated AlGaAs laser diodes and shows that the average time required for the 20% increase in I_{TH} increases from approximately 500 hours at 100^oC to about 5000 hours at 70^o C. Extrapolating the data, it can be seen that at 22^oC (approximately room temperature) the time increases to about 10^6 hours. One other factor which must be considered in semiconductor laser design is ohmic contact degradation which is common to all semiconductors at high current densities. This degradation results from a change in the thermal and electrical resistances between the semiconductor materials and the heat sink over time. The orientation of the chip relative to the mount, as well as the solder type and soldering method have an effect on the degradation. For a more detailed discussion of semiconductor laser reliability see reference [4].

The conclusion that can be drawn from the above discussion is that significant benefits can be accrued in terms of laser efficiency and lifetime by maintaining semiconductor laser diode operating temperatures relatively stable, at or below room temperature. Orders of magnitude increases in laser lifetimes can thus be achieved. Various other laser parameters may change with diode aging and use. The stability of output power is not the single most critical utility in long haul communications systems.

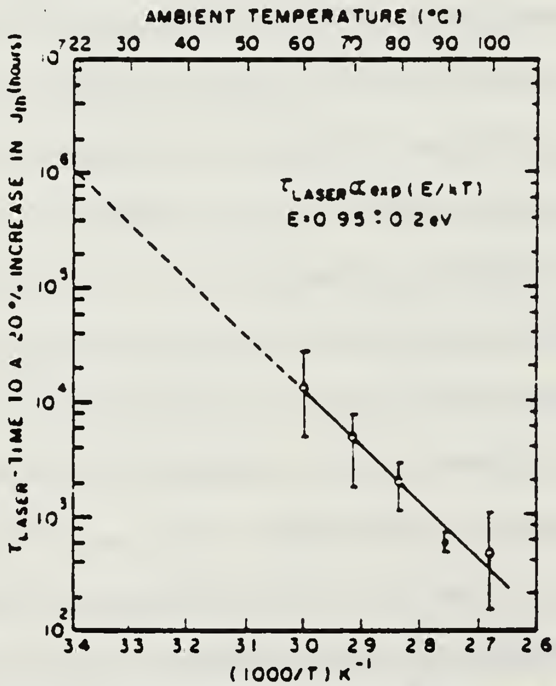

Figure 2.5. Laser Lifetime to a 20% Increase in Threshold Current as a Function of Temperature (from Ref. 2)

A few other critical issues should be mentioned, including [Ref. 2: p. 58]:

1. Constant output linearity.
2. Lateral mode changes resulting in a reduced fiber coupling efficiency.
3. Changes in Spectral width over time.
4. Induced oscillations in optical emmission.

Available data obtained at RCA laboratories suggests that substantial power degradation over time also produces lateral mode changes at a given current above threshold. Since these lateral mode changes shift with drive current, this would surely result in kinks in the power-current characteristic curves of the laser yielding nonlinear behavior of the degraded laser towards end of life. These changes, however, would not necessarily result in a significant loss of fiber coupling efficiency because the angular divergence of the lateral beam undergoes only modest changes. Spectral width may also increase with time [Ref. 2:p. 59].

By far the most troublesome issue concerns laser oscillations. It has been found that some laser diodes initially free from output oscillations developed oscillations over time despite only minor changes in I_{TH} or quantum efficiency. The self pulsations (at frequencies of 300-600 MHz) occurred during continuous operation. These oscillations are produced primarily due to the non-uniform carrier density along the cavity length caused by defects in the active layer, non-radiative recombination at mirror facets, or local variation in the current injection caused by processing defects. Oscillations have been found to increase as drive current increases. These same findings also noted that optical power emitted from the two laser facets changed asymetrically over time. This problem would be most serious in transmission systems using "optical feedback" (via a monitor photodiode) where the light emitted from the back laser facet is used to maintain the D.C. bias at threshold. It was noted, however, that only some lasers exhibit this effect and therefore, can be concluded that it is not an inherent laser property but most likely a defect-induced characteristic which needs to be identified and eliminated. From the preceeding discussion it can be seen that laser reliability and performance can be enhanced by careful design of power supplies, proper operation and operating conditions. With this in mind, the next section discusses a very unique component which could be added to a laser diode transmitter power supply to provide a much more reliable and operationally efficient transmission system, a D.C. powered thermoelectric cooler.

E. THERMOELECTRIC COOLERS

Thermoelectric (TE) coolers are solid state heat pumps without fluids, gases or moving parts. The primary purpose of the TE cooler is to take heat away from a body to be cooled and carry it towards a heat sink. The main reasons for considering the use of a TE cooler (besides the need to maintain the laser diode at a relatively cool and stable temperature) are its small size and weight, low operating voltages, and wide range of heat pumping capacity. Another factor is the level of reliability of these components. Mean time between failure (MTBF) tests have yielded results on the order of 100,000 hours at temperatures exceeding 100°C and 200,000 - 300,000 hours at room temperatures. [Ref. 5:p. 8]

In our application, the Lasertron QLM-1300-SM-BH laser has incorporated into its package a thermoelectric cooler to maintain the semiconductor laser at a nominal operating temperature of approximately 25°C, thereby maintaining the laser threshold current at 49 mA. Figure 2.6 shows a single couple cross-section of a typical TE cooler. The coupling is formed by the interaction of the two dissimiliar metals (n-doped and p-doped bismuth telluride) to give rise to the absorption and liberation of heat as D.C. current flows across the junction.

Practical use of these TE couples entails combining multiple couples into a single module. These couples are connected in series electrically and in parallel thermally. These unique semiconductor units are commercially available in many sizes and heat transfer capacity. In order to ascertain which specific device or group of devices should be used for a particular application (assuming a cooler was not part of the laser package), three system parameters must first be determined. These are the desired operating temperature of the unit to be cooled (T_c), the temperature of the heat sink (T_h) and the amount of heat to be removed or absorbed by the cold surface of the cooler (Q_c).

All thermal loads on the TE cooler must be accounted for. These loads consist of the active I^2R heat load of the laser and heat loads of surrounding electrical components which contribute radiant heat to the ambient surroundings.

Once these parameters have been quantified, the charts shown in appendix A can be used to determine which type of TE module should be used and the operating D.C. current to remove the desired heat capacity. Power supply stability for the cooler is of the utmost importance as the TE device is a D.C. device and any A.C. component could be detrimental. It is strongly recommended that A.C. ripple be kept below 10%. [Ref. 5:p. 5]

Temperature control can be handled in two ways, open or closed loop. In the closed loop scheme, the cold junction (side being cooled) is used as the basis for control. This temperature is compared to a reference temperature (known as the setpoint temperature) which subsequently controls the voltage across the TE module, thereby adjusting the heat pump capacity of the device. In the open loop method, the power supply is adjusted manually to maintain the temperature difference at zero.

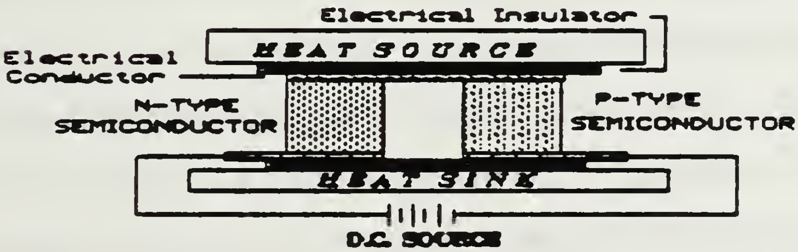

Figure 2.6. Cross Section of a Single Couple Thermoelectric Cooler (from Ref. 5)

F. LASER MODULATION

1. Modulation Considerations

Semiconductor lasers are ideal optical transmitters in many respects as they are well suited for direct modulation in an ON/OFF format with relatively high optical power. They permit high coupling efficiencies, thereby allowing more optical power to be launched into a given fiber and subsequent greater distances between repeaters in a long haul transmission link.

GaAs lasers are characterized by fast response with rise and fall times of less than one nanosecond. This can permit modulation bandwidths of greater than one gigahertz. Proper choice of drive circuitry will minimize this rise time. In order to achieve the optimal analog modulation of the laser (i.e., high speed, minimum turn-on delay), the source is biased to an operating point on the linear portion of the output curve just above I_{TH} and modulated about this point. This operating condition is shown in figure 2.7. A tradeoff that is made in doing this however, is the fact that the average power dissipated by the laser will be greater, resulting in decreased unit efficiency. Another drawback of this procedure is faster aging of the laser source. For these reasons, the bias current should be kept as low as possible, while still maintaining the operating point on the linear portion of the curve above threshold. A major problem which must be compensated for in continuous wave (CW) operation of laser diodes is maintaining the stability of the operating point over time. Heating and aging both affect I_{TH}. Laser diodes possess a positive temperature coefficient of approximately one percent change in I_{TH} per degree centigrade [Ref. 2:p. 166]. In order to compensate for these effects, two different feedback mechanisms are provided, temperature and optical power (via the monitor photodiode) which adjust the drive current bias point to maintain the operating point on the linear portion of the output curve. For example, as laser operating temperature increases, a thermistor circuit senses the change and feeds back a signal to a thermoelectric cooling circuit (discussed earlier) which provides greater cooling capacity to the laser diode TE cooler resulting in a lower operating temperature. With the monitor photodiode, one can utilize its current output (proportional to optical power out of the laser diode) as a feedback signal to the driver circuit to produce a negative feedback closed loop system. This circuit would then automatically adjust the drive current to the laser diode based on an optical power setting and the actual optical power being launched into an optical fiber.

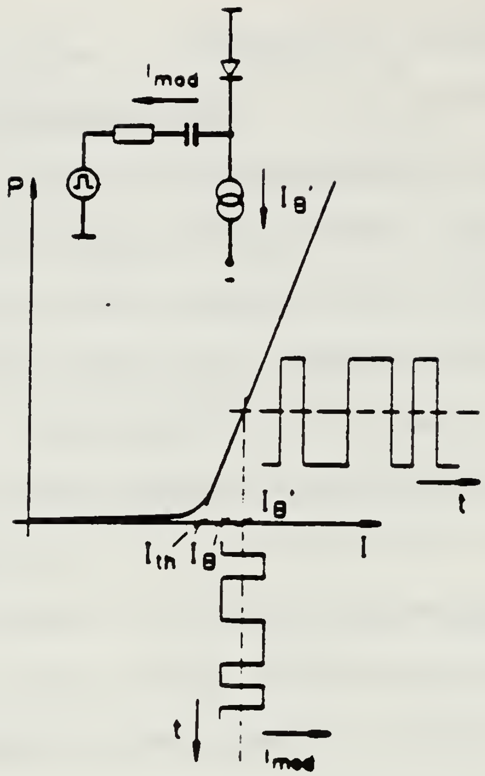

Figure 2.7. Operating Point Adjustment for Laser Modulation Above Threshold (from Ref. 1)

2. Modulation Formats

The particular modulation format chosen for a design is extremely important as it can enhance or degrade the performance of the particular communications system as a whole. The format chosen should tolerate system attenuation and/or signal degradation arising from fiber dispersion and various sources of noise throughout the system. Binary Digital modulation, Pulse Code modulation (PCM), and adaptive Delta modulation (ADM) are ideal in these respects for fiber optic communications because of the high signal-to-noise ratio's (SNR) and subsequent low bit error rates (BER) characteristic of these formats. This is primarily due to the fact that the binary signal tolerates large amounts of attenuation and signal degradation without the information content, since only a pulse/no pulse decision must be made at the receiver.

The digital format however, becomes quite burdensome in regards to bandwidth. For PCM, an analog signal must be sampled at a minimum of two times its highest frequency component (i.e., Nyquist rate > $2f_{max}$). As an example, a signal with f_{max} = 6MHz would have to be sampled at a rate of 12×10^6 samples per second. This is the theoretical minimum sampling rate to avoid aliasing. Most systems are sampled at three or four times the maximum frequency component. If 16 bit coding is desired for high resolution (SNR) we we would then require a data rate of 192 MB/second. (16 bits/sample x 12×10^6 samples/second)

In spite of the advantages of digital signaling, analog, CW applications such as direct intensity modulation (IM) offer simplicity and lower cost (no code/decode equipment required at the transmitter or receiver). One problem, however, with laser diodes in CW IM applications is excess noise. Near threshold, the light output has wideband noise of an amplitude greater than shot noise superimposed on it.

This results in reduced SNR's up to about the 10% point above threshold. At this point the excess noise drops off to the shot noise level in most lasers. Some lasers however, maintain this excess noise well above the 10% point above threshold. The excess noise problem is most common in regions of kinks (discussed earlier). One other phenomenon causing modulation (IM) problems is the self pulsations mentioned earlier. The modulation index of these pulsations can be quite large (nearly 100%) and therefore potentially devastating in IM applications.

3. <u>Laser Spectral Behavior Due to Modulation</u>

Various types of spectral changes may occur in the semiconductor laser output being modulated (as opposed to an unmodulated laser). These changes include the following:

1. The multimode character of the spectrum becomes more pronounced.
2. Mode jumps may occur.
3. Spectral lines become frequency modulated.

Due to fiber dispersion, cases one and two restrict the bandwidth that can be achieved. This becomes especially critical in transmission systems at wavelengths of 1.5 um (dispersion at this wavelength amounts to approximately 16 ps/km-nm).

Spectral changes are caused by changes in temperature and carrier density in the active region occurring with modulation. The increase in temperature causes a reduction in the energy gap of the semiconductor crystal. The result of this reduction is a shift of the gain maximum to higher wavelengths. For GaAs the shift is approximately 0.25 nm/K [Ref 1:p. 29]. At modulation frequencies below 10 MHz, the changes in temperature dominate, while at higher frequencies carrier density changes are dominant. This variation in the maximum gain wavelength leads to mode hopping.

Case 3 refers to frequency modulation of individual longitudinal modes being superimposed on to the intensity modulation. This phenomenon is due to the dependence of the refractive index of the active region of the laser on temperature and charge carrier density. An increase in temperature causes an increase in the refractive index while an increase in charge carrier density causes a decrease in the refractive index. This leads to smaller or larger frequencies, respectively. As a result, the spectral width of the individual line may be significantly larger than that of the modulation signal.

Digressing back to the beginning of this section, mode hopping occurs when semiconductor lasers are modulated at high bit rates. It is therefore desirable to stabilize the modulated laser at one longitudinal mode. This would result in an increased capacity (BW-distance product) of the transmission system.

Numerous methods exist for creating a Dynamic Single Mode Laser (DSM). These methods include coupled resonators, injection locking, short laser cavities, and frequency selective feedback. The latter method replaces reflections on the laser facets with partial or complete reflection at integrated gratings. This group of lasers are known as Distributed Feedback (DFB) Lasers or Distributed Bragg Reflector (DBR) lasers. A diagram of the structure of the DFB and DBR laser is shown in Figure 2.8. In all of these methods, the secondary modes show much higher losses than

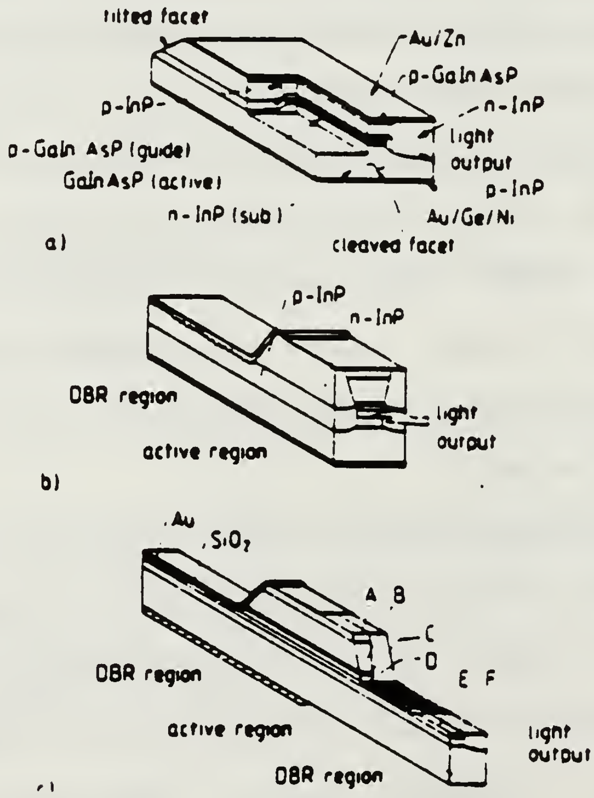

Figure 2.8. DFB and DBR Laser Structure
(from Ref. 1)

the primary mode. Side mode intensities typically yield less than 1% of the main mode intensity. A more detailed discussion of DFB and DBR lasers along with discussions of other methods for achieving DSM stability can be found in reference 1.

G. LASER MODULATION CIRCUIT CONSIDERATIONS

One critical element in the design of a laser diode modulation circuit is the determination of the input impedence and equivalent circuit of the laser diode and packaging. The small signal equivalent circuit diagram of a typical laser diode is shown in figure 2.9. This figure shows not only the equivalent circuit of the laser but the parasitic elements of the package. The current i_s in the series circuit R_{s1}, L_s, and R_{s2} corresponds to the light output power. The values of the parasitic elements of the active layer are dependent on the laser drive current. Typical values for these elements are given in Table 2.1.

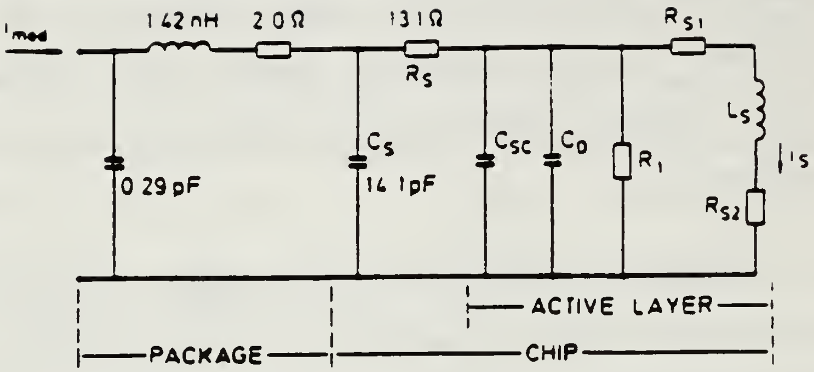

Figure 2.9. Small Signal Circuit of a Typical Laser Diode (from Ref. 1)

Table 2-1.
Parasitic Element Values for a Packaged BH Laser (from Ref. 1)

I(mA)	C_{SC}(pF)	C_D(pF)	R_1	R_{S1}(mΩ)	R_{S2}(uΩ)	L_S(pH)
20	10	380	1.23	23.4	34.0	7.07
25	10	381	0.829	24.1	11.8	4.19
30	10	382	0.628	24.7	6.0	3.01

The capacitance between contacts and series resistance are accounted for by C_s and R_s in figure 2.9. With laser current above threshold, the impedance of the active layer of the laser diode is relatively low compared to the impedance of the remaining circuit (on the order of 0.25%).

Therefore, the active layer can be modeled as a short circuit. Because of the direct relation between drive current, optical power and the low laser impedance, the modulation drive circuit should be a current source with a high internal impedance as compared to the input impedance of the laser. [Ref. 1:p. 33] Summarizing the above, laser diodes present a low impedance when "on" (lasing) and a high impedance when "off". Modulation signals may encounter an impedance mismatch at the laser diode and be reflected back toward the source. If the reflected energy is not entirely absorbed by the source, undesirable effects may occur. In the case of analog modulation where a continuously varying signal is added to a fixed D.C. bias, and the modulation signal is reflected from the diode towards the generator, there may be a phase difference between the generator drive and the reflected signal. If the output impedance of the generator matches the impedance of the transmission line to the source, the reflected energy will be absorbed. If all of the energy is not absorbed it will again travel down the line to the laser permitting standing waves to develop causing the power to the laser diode to vary with cable length and drive frequency. This would tend to cause unwanted distortion of the optical signal and may even overdrive the laser. Because of these potential problems, the following design considerations should be made: [Ref. 6:p. 8]

1. Modulation signal generator output impedance should match line impedance.

2. D.C. bias is combined with the high frequency modulation signal as close to the laser diode source as possible.

3. A current limiting device should be incorporated into the drive circuit design to prevent overdrive of the laser diode, resulting in catastrophic damage to the laser.

H. LASER FREQUENCY RESPONSE/TRANSIENT RESPONSE

The final matter to be addressed with regards to laser modulation is the response of the laser to high frequency modulation. Since this design covers CW operation, a laser biased above threshold having a sinusoidal modulation superimposed on the steady current will be analyzed. In most lasers, the modulated optical power is found to go through a resonance. This resonant frequency depends on the laser bias level. The cause of the resonance is the interaction between the optical power density and the excess carrier density in the resonant cavity (active region of the crystal). An increasing current leads to an increase in the carrier concentration after a short time delay. This then results in an increase in the radiation recombination density, and after a further delay stimulates recombination and causes carrier concentrations to fall. It is because of the time delays that the fall overshoots an equilibrium value and oscillation occurs. The optical frequency, then, is a function of the optical decay time constant, t_{ph}, and the carrier recombination time constant, t_{sp}. The interactions are non-linear and the resonant frequency depends on the amount by which the laser bias exceeds threshold. The resonant frequency curves can be fitted to the following relation [Ref. 7:p. 342]:

$$\frac{P(w)}{P(0)} = \frac{w_o^2}{(w_o^2 - w^2) + jBw} \qquad (2\text{-}4)$$

where

$P(w)$ = Optical power density as a function of modulation frequency

I_o = Laser bias level

w_o = Resonant frequency

w = $2\pi f$ (Sinusoidal modulation frequency)

B = $I_o/t_{sp}I_{th}$

w_o^2 = $(I_o - I_{th})/t_{sp}t_{ph}I_{th}$

The optical time constant, t_{ph}, is basically the average photon lifetime within the cavity, and can be found by the following relation [Ref. 7:p. 342]:

$$t_{ph} = \frac{u}{c\,\alpha_{total}} \qquad (2\text{-}5)$$

For GaAs u = 3.6 and a typical value for α_{total} is 2000 m^{-1}. This results in an optical time constant of approximately six picoseconds. The carrier recombination time constant, t_{sp}, can be assumed to be approximately 10 nanoseconds. Therefore, with $I_o = 1.2\ I_{th}$, the resonant frequency would be about 0.3 GHz.

Another situation which is a function of radiation/ carrier resonance is laser "switch-on" characteristics and behavior. Because of the laser resonance, following the switching on of modulation drive current, the laser output exhibits a "ringing" transient response as shown in figure 2.10.

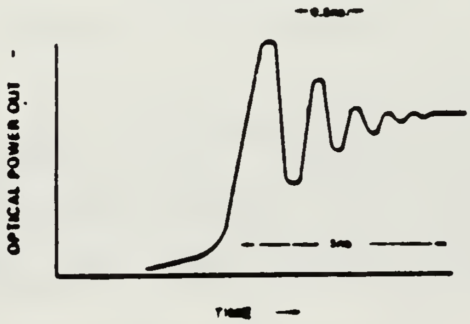

Figure 2.10. Transient Response of a Typical Laser Diode (from Ref. 6)

Although the maximum current level has some effect on increasing the ringing frequency and narrowing the optical spectrum, it is the level of the bias point which is the primary factor. As the bias current is raised from zero towards and past threshold, the delay time decreases, the level of ringing is steadily damped out, and the average spectral width is significantly reduced.

III. SCHEMATIC DESIGN AND DESCRIPTION

A. UNIT DESCRIPTION AND FUNCTIONAL LAYOUT

The approach to the design of this laser diode drive unit consisted of separating the unit requirements into functional blocks. Each of these blocks was then designed independently with interface requirements for each sub-unit taken into consideration. This approach provided for an efficient method of incorporating the many desired features and laser drive requirements into the aggregate unit. Construction of the unit was also made more efficient as each sub-unit was put together and tested independently of the others. This resulted in a thesis project made up of many smaller circuit design projects.

1. Functional Layout

A functional block diagram of the laser drive unit is shown in figure 3.1. As can be seen, there are basically four functional blocks to this design. These include the power supply, front panel control and display, laser drive circuit and modulation circuit. A fifth block is shown which represents the laser diode and its associated feedback signals. A complete description and schematic of each functional block is included later in this chapter.

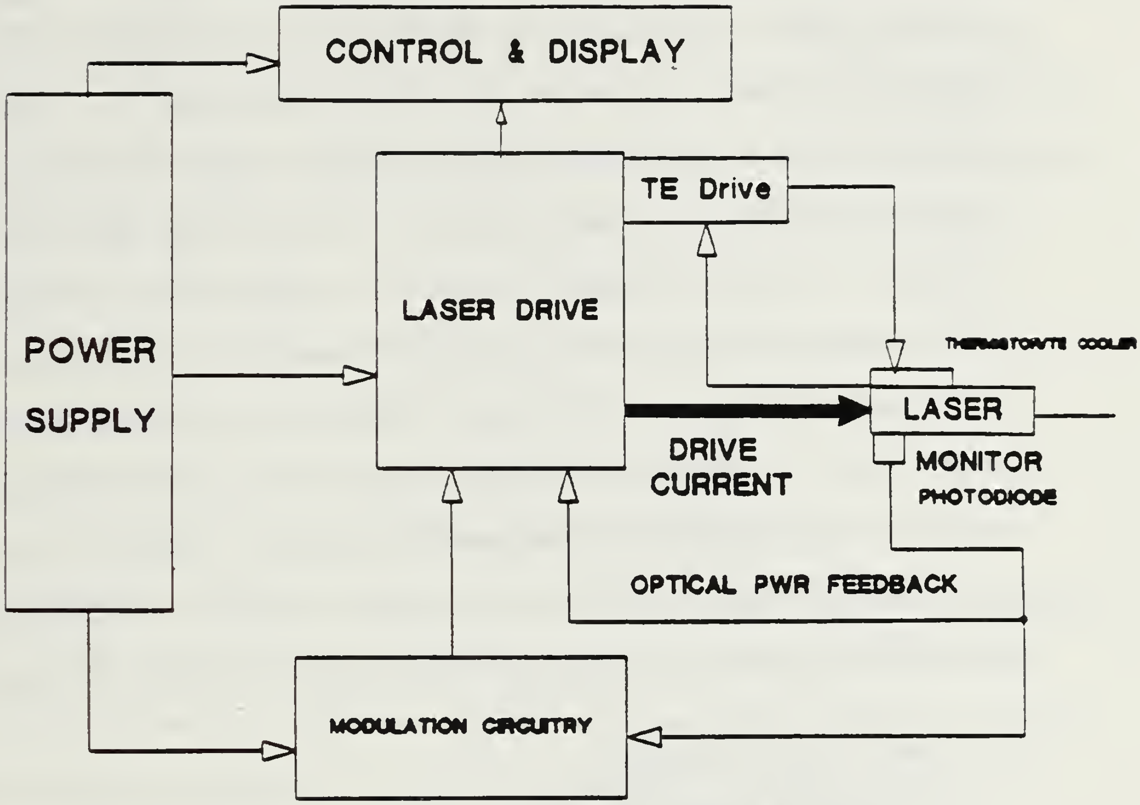

Figure 3.1. System Block Diagram

2. __Subsystem Interfaces__

Figure 3.1 shows that the unit's power supply circuitry provides D.C. power to all of the remaining subunits. The primary voltage levels provided are +\-5Vdc, +\-12Vdc, and of course a common ground. The laser drive circuit produces the appropriate D.C. bias current and provides it to the laser. Various taps off of the drive circuitry are made and are able to be sent to the front panel display unit (i.e., bias current, laser temperature, optical power, etc.) via a set of DIP switches. The modulation circuitry is connected in parallel with the laser diode and provides a modulated input to the laser diode superimposed onto the D.C. bias current. As can be seen from the diagram, various feedback signals are sent back to the drive circuitry from the laser diode. These signals include laser temperature (from thermistor) and optical power from the rear facet of the laser diode onto the monitor photodiode. Both of these signals are used to control the D.C. bias current driving the laser over its lifetime, and the operation of the TE cooler via control of its drive current.

B. POWER SUPPLY DESIGN

1. Voltage Requirements

The primary voltage requirements of this unit are +\-5Vdc and +\- 12Vdc. Since the source of power for this project is a set of 6V batteries, DC to DC conversion and regulation becomes important. A key element, however, in DC to DC conversion process is conversion efficiency. Typically, the conversion process causes significant power losses which must be accounted for in any system power budget employing DC to DC conversion.

2. Circuit Description

In this design, it is required to produce 5V from the 6V battery sources. It is also important that all voltages supplied to the system be regulated. Therefore, to achieve a regulated +5Vdc, a Motorola MC7805 three terminal positive voltage regulator is used. There are many characteristics which make this a very good regulator for our purposes including:

1. Output current capacity in excess of 1 amp
2. Little or no external components required
3. Internal thermal overload protection
4. Internal short circuit current limiting

A schematic of this 5V regulating circuit is shown in figure 3.2. As can be seen, a common ground is used between the input and output voltages (this is required) with the input and output capacitors primarily employed to improve the transient response of the circuit.

In order to produce the -5Vdc (regulated), a Linear Technology LT1054 switched capacitor voltage converter and regulator was employed. The primary advantage of this device is its high output current (up to 100 mA) with very small voltage loss (1.1 volts @ 100 mA). The LT1054 also provides voltage regulation, a feature not normally available on-chip with switched capacitor voltage converters.

Other key features include:

1. Operating range 3.5V to 15V
2. External shutdown capability
3. Ability to be paralleled

The internal oscillator (switched capacitor switching frequency) of the LT1054 runs at a nominal frequency of 25 kHz. This corresponds to the frequency at which voltage losses are at a minimum.

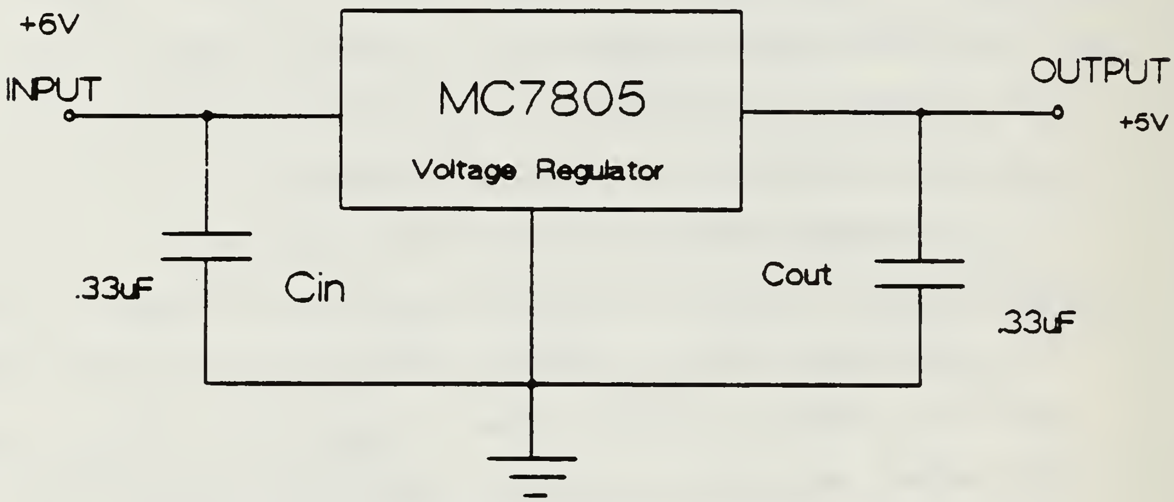

Figure 3.2. Power Supply 5V Regulator

A schematic diagram of the LT1054 used as an inverter/regulator is shown in Figure 3.3. As can be seen, the input voltage is the 6V battery with an output voltage of -5Vdc. The resistor R1 is 20k ohm for any desired output voltage (as per manufacturers data sheet recomendations). Frequency compensation is accomplished by adjusting the ratio of C_{in} to C_{out}. The optimal ratio is approximately 1/10. In order to provide good load regulation, C1 should be approximately 0.047 uF for all output voltages. Regulation performance of the LT1054 is very good with peak-to-peak output ripple determined by the output capacitor and the output current.

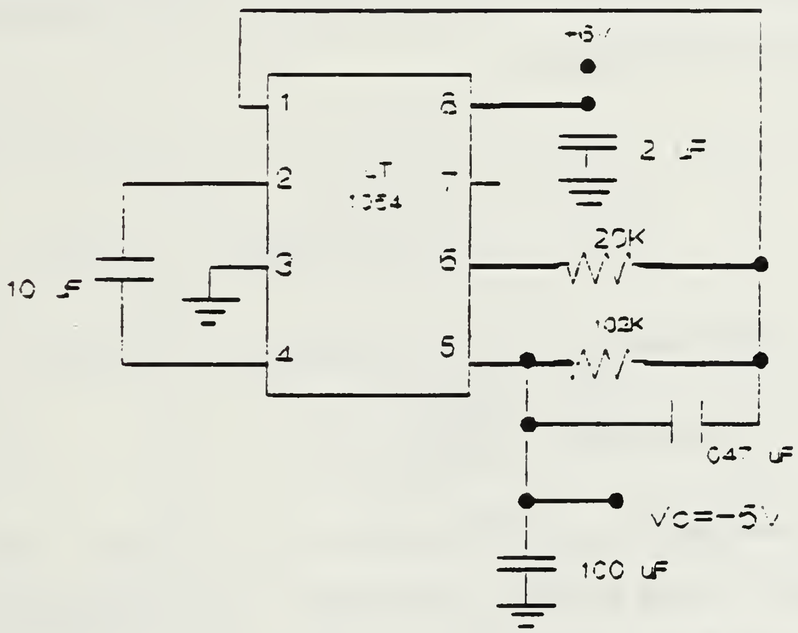

Figure 3.3. Inverter/Regulator Circuit for -5Vdc Output

This ripple voltage can be approximated using the following relation:

$$V_{pp} = \frac{I_{out}}{2fC_{out}} \qquad (3\text{-}1)$$

where

I_{out} = Output Current

V_{pp} = Output peak to peak Ripple

C_{out} = Output Capacitance

f = Oscillator Frequency

Using this relation and actual circuit values from figure 3.3, the following ripple voltage is determined for the circuit constructed:

$$V_{pp} = \frac{100\ mA}{2(25kHz)(100uF)} = 20\ mV$$

R2 is computed using the following relation:

$$R2 = R1\left\{\frac{|V_{out}|}{1.21} + 1\right\} \qquad (3\text{-}2)$$

With a desired V_{out} = -5Vdc and R1 = 20k ohm, the above relation yields an R2 = 102k ohm. This configuration yields V_{out} = -5V @ 100 mA.

With +\-5Vdc now provided, there still remains the problem of generating a regulated +\-12Vdc from the 6V battery. For this the LT1054 was again employed using two of them to provide both the required voltages. Figure 3.4 shows the schematic of this circuit. This configuration of LT1054's is designed to provide 25 mA @ +12Vdc and 25 mA @ -12Vdc. Since more than 25 mA at each voltage is required, this circuit was duplicated four times and connected in parallel to provide 100 mA of output current capacity at each voltage polarity. Actual results netted 32mA of output current at both voltages for each of the configurations shown in Figure 3.4. The power supply unit was then loaded with the remaining subunits of the entire system and operated satisfactorily with little or no voltage drop while loaded.

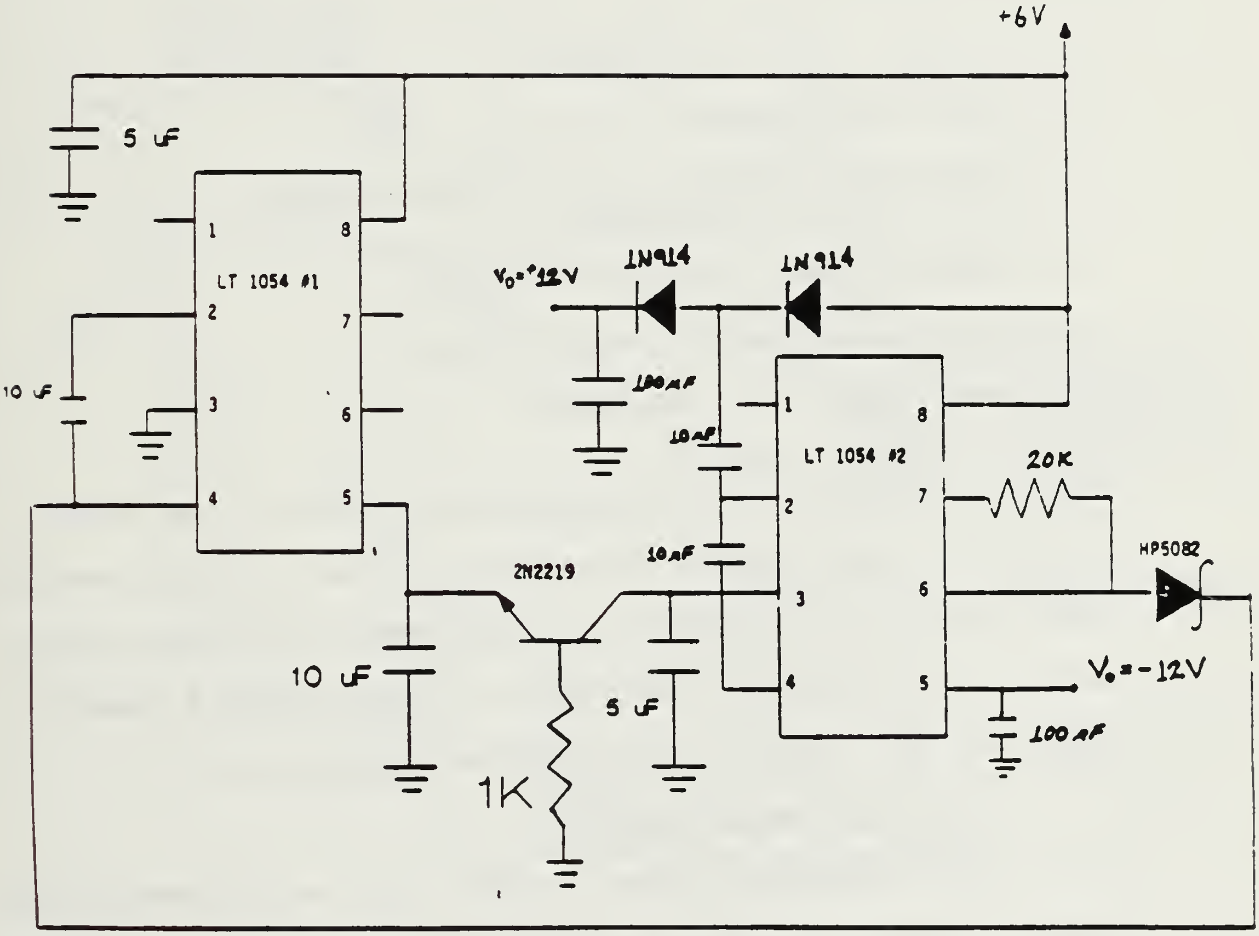

Figure 3.4. **+6V to +\-12V Converter**

C. FRONT PANEL DISPLAY

1. Functional Description

The primary component of the display portion of the display sub-unit is an autoranging digital multimeter (DMM). This DMM is switchable between the various parameters that need to be measured and displayed from the other portions of the laser drive unit. The following parameters are available for display:

1. Current Limit Setting
2. Laser Bias Current
3. Total Drive Current (Sum of Bias Current and Modulation Current)
4. Optical Power (From Photodiode)
5. TE Cooler Setpoint Temperature
6. Laser Operating Temperature

These parameters are received from taps off of the respective test points in the circuit and routed to a six position switch for operator selection of the desired display parameter. The output of the switch is sent to pin 3 (analog input) of the MC14433 A/D converter chip.

2. Circuit Description

The function of the display unit centers around the Motorola MC14433 analog-to-digital converter. This single chip A/D converter utilizes a modified dual ramp integrating technique to perform the A/D conversion. The single input to the chip provides for conversion of all ranges and functions in analog voltage/current format. The output is 3 1/2 digit multiplexed binary coded decimal (BCD), containing the digits, polarity, and over or under-range information. Figure 3.5 shows the schematic diagram of the display unit.

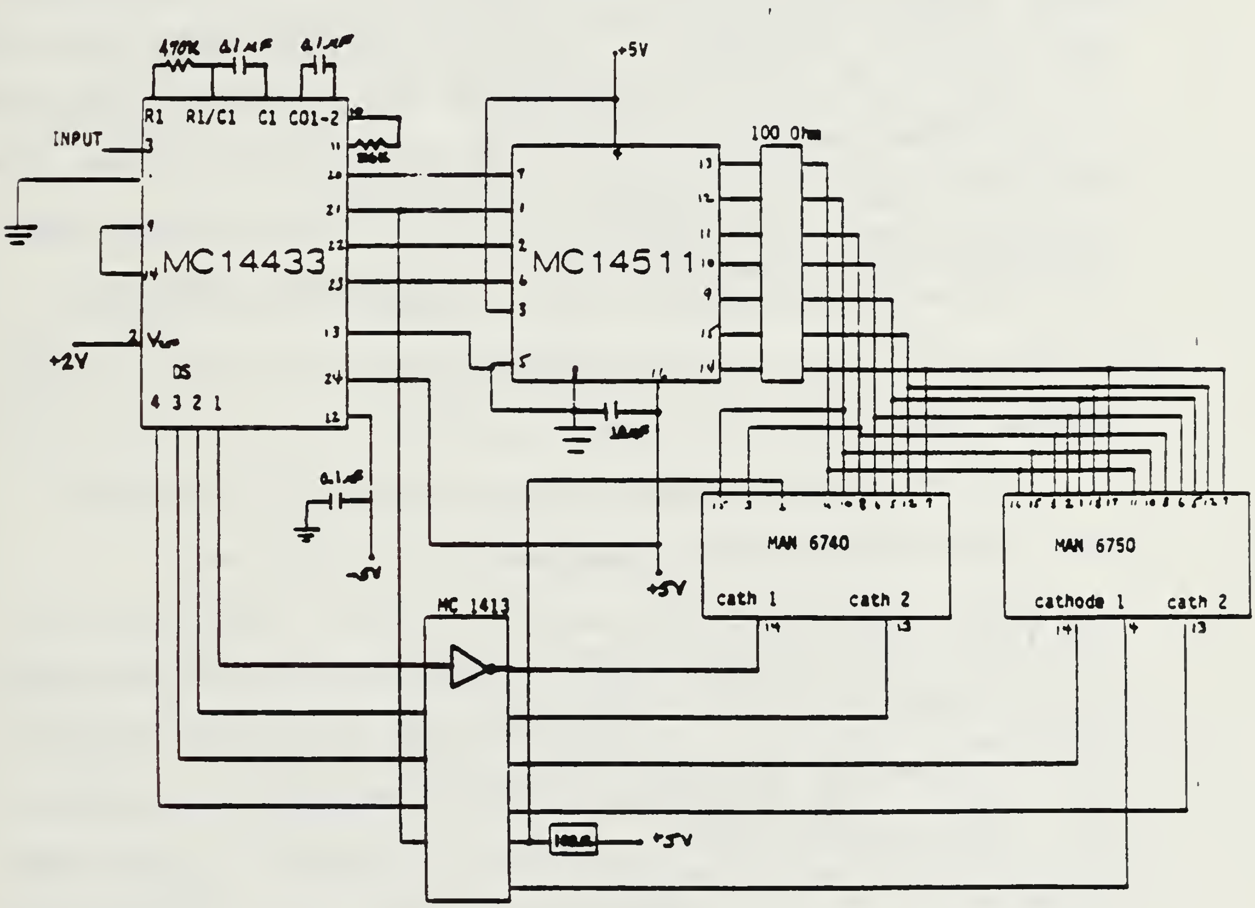

Figure 3.5 DMM Display Unit (adapted from Ref. 8)

The MC14433 requires an external reference voltage for use in performing the ratiometric integrator computation conversion. The desired input range is 0 to 1.999V and 1.999 mA to 1.999 Amps. The display requires a low voltage power supply of +\-5V, which is provided by the power supply unit described earlier. The critical external components of the MC14433 include the 470K ohm integrator resistor which operates in conjunction with the 0.1 uF integrator capacitor. These components are connected between pins 4, 5, and 6. The 0.1 uF capacitor connected between pins 7 and 8 acts as an offset capacitor. The 316K ohm resistor between pins 10 and 11 sets the frequency of the internal clock. This frequency can be determined by the following relation:

$$f_c = 0.22 \times R_c \qquad (3-5)$$

where

f_c = Desired clock frequency (in Hz)

R_c = Clock setting resistor

The total A/D conversion time is approximately 16,400 clock periods [Ref. 9:p. 3], therefore, the conversion rate can be determined by dividing the clock frequency by 16,400. The configuration shown in figure 3.5 yields a clock frequency of f_c = .22 x 316K ohm = 69.5 KHz. and the conversion rate is 69.5 KHz/16,400 = 4 conversions per second.

Other major components in this design include the Motorola MC14511 BCD-to-7 segment driver, the MC1413 lamp driver, and the MAN6740 and MAN6750 7-segment LED display units. The MC14511 receives from the MC14433 chip, BCD data and provides drive current to each of the MAN6740 and MAN6750 LED displays according to the BCD input data. Figure 3.6 shows the pin to segment drive configuration. The Motorola MC1413 is primarily an array of darlington transistors which primarily function to provide drive for the LED display cathodes. This function is accomplished by utilizing the digit select (DS1-DS4) outputs of the MC14433. The digit select output is high when the respective digit is selected for display. The multiplexed BCD outputs contain three digits of information during DS2, 3, 4 with the 1/2 digit, over and under-range information, and polarity available during DS1.

The constructed unit was tested over its full range of operation. Since a reference voltage of two volts was chosen, this allowed for an input voltage range of 0 to 2.0 volts. Full scale output from 0 to 1.999 volts was achieved with good response time (A/D conversion time) between input and output. Accuracy of the digital output was within one percent (0.010).

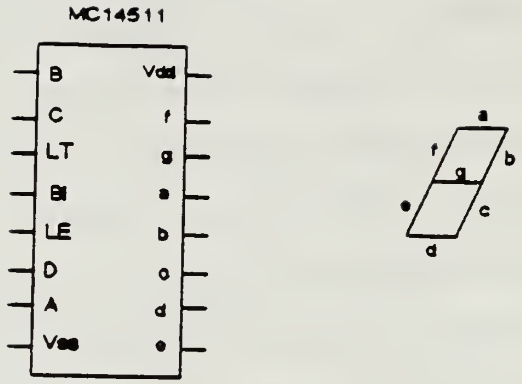

Figure 3.6. Pin to Segment Drive Configuration
(from Ref. 14)

D. LASER DRIVE CIRCUIT

1. Description

Of primary importance in the design of this driver circuitry was the stability and accuracy of drive current supplied to the laser diode. This is to ensure safe operation of the laser diode at the desired operating point. Numerous protective and control features were incorporated into the circuit to achieve this. These features include:

1. Current Limit capability
2. Negative feedback of optical power
3. Switch on/Switch off transient protection (Control logic)
4. Low pass filtering of bias current to filter high frequency current components
5. A.C. coupling to modulation circuit
6. Seperarate control of D.C. bias and A.C. modulation current

Figure 3.7 shows a schematic diagram of the laser diode drive circuit. The primary driving elements of this circuit are the Elantec EL2020 current feedback amplifier and the EL2003 line driver. The control point of the drive circuit is the EL2020. This element acts as a comparator by using the bias current setpoint and the current feedback from the monitor photodiode (discussed later) to generate a control signal to the EL2003 driver which subsequently increases or decreases the bias current to the laser diode. The maximum current that can be supplied to the laser diode from this circuit is 100 mA and is limited by the EL2003 drive capacity.

The RC network consisting of a 56 Kohm resistor and a 1.5 uF capacitor provides for a finite rise time of laser current. The RC time constant is 84 milliseconds. Downstream of the EL2003 is a low pass filter (LC network) to protect the laser diode from current transients as the operating point should be kept as stable as possible. The relay in parallel with the laser diode is controlled by the slow start control logic (discussed later) and is primarily employed for laser protection at startup and shutdown. The 2N4360 p-FET at the input of the EL2020 acts as a switch for the drive circuit and provides for control of the bias current circuit during power up. The p-FET possesses a very large OFF resistance and a very small ON resistance so as not to have a great effect on the input impedance of the EL2020. The operation of this 'switch' is also controlled by the slow start control logic. The actual bias current supplied to the laser diode is controlled by the 2 Kohm potentiometer feeding the input of the EL2020. This potentiometer performs by changing the voltage divider resistance which increases or decreases the voltage at the non-inverting input of the EL2020. This configuration yields a voltage controlled current source which changes the drive at the input of the EL2003 line driver.

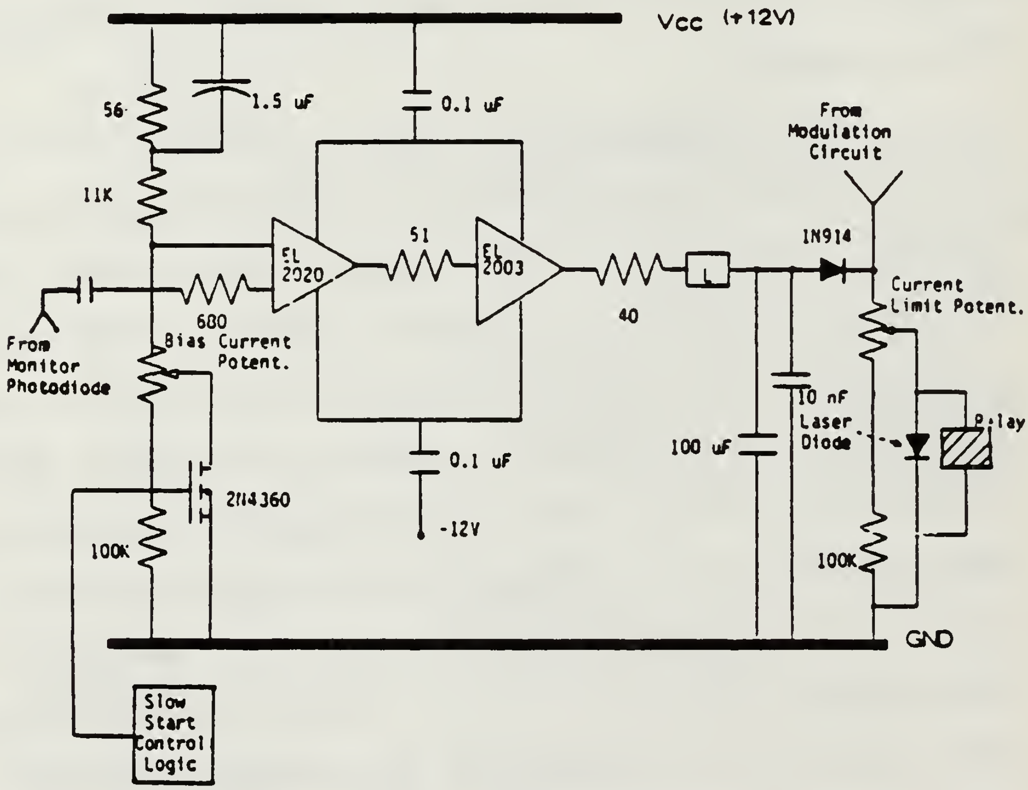

Figure 3.7. Laser Drive Circuit/Bias Current Supply (adapted from Ref. 11)

This design also utilizes the capabilities of laser diodes to provide a current feedback of laser optical power via an in line monitor photodiode. This signal is routed back to the inverting input of the supply op-amp (EL2020) via a set of three transistors configured as a variable gain current mirror. This current mirror circuit is shown in Figure 3.8. The purpose and function of the current mirror is to change the polarity and level of current from the monitor photodiode. This is required as the photodiode is normally operated in a reverse biased mode. The current transfer ratio is set by the 10 turn precision potentiometer. The resulting circuit provides a control setting for the optical power output of the laser diode.

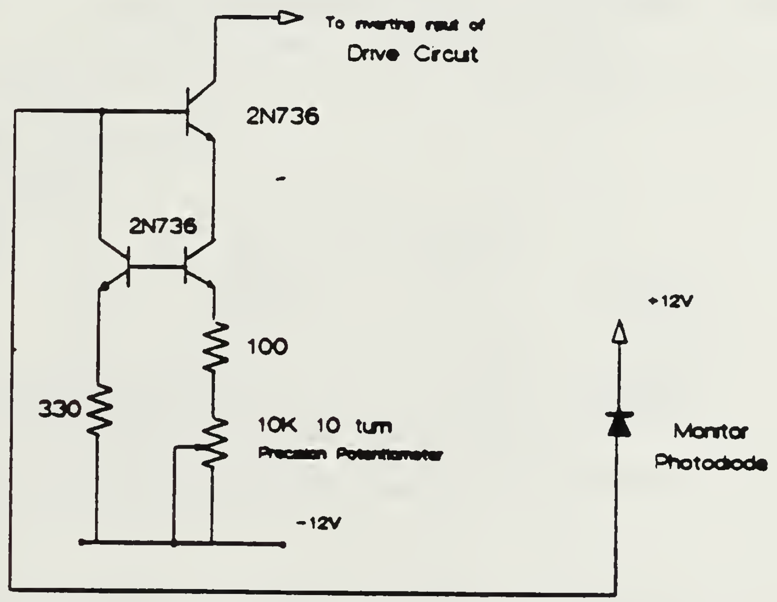

Figure 3.8. Current Mirror Circuit (from Ref. 9)

As previously mentioned, the p-FET posesses a very small ON resistance and provides for control of the source circuit current during powerup. The relay contact shorts the laser connections in dangerous situations (i.e. transients, power failure, etc.) and is controlled by the associated logic circuitry which is shown in Figure 3.9.

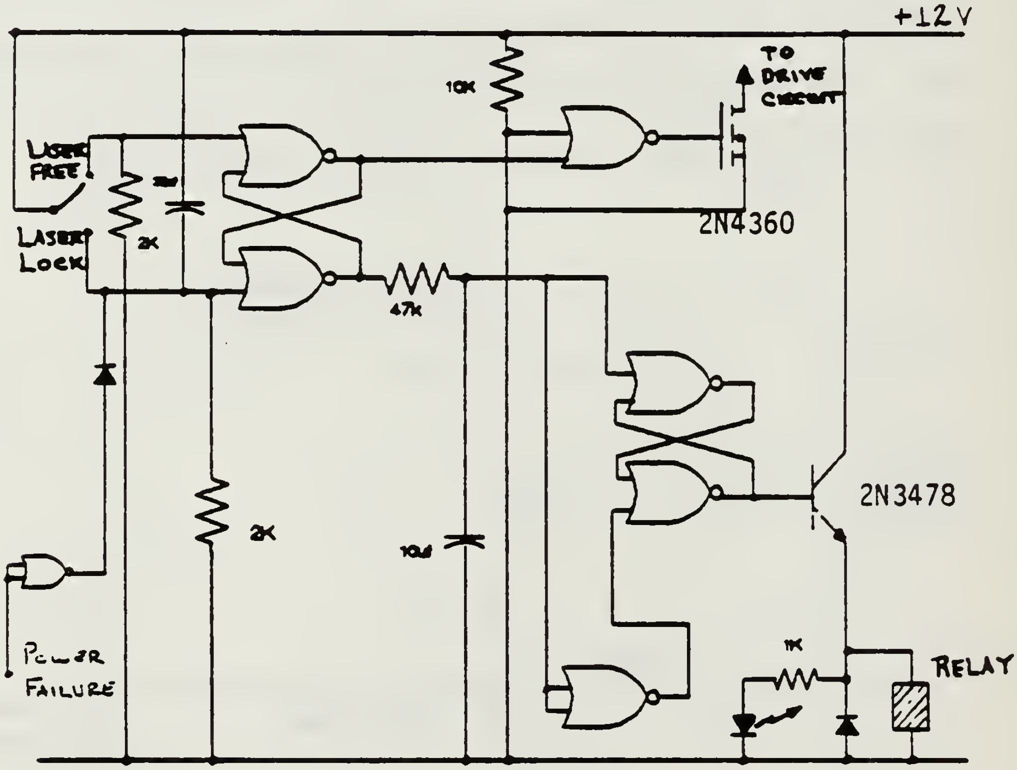

Figure 3.9. Switch On/Switch Off Control Logic (from Ref. 11)

The overall operation of the control logic, relay, and laser drive is as follows:

1. Switching laser "on"

    a. Ensure power "on"

    b. Laser drive level set

    c. T0: Command switch set to "laser free"

    d. T1: Relay is powered and contact opens

    e. T2: Laser bias current rises slowly to preset level

2. Switching laser "off"

    a. T3: Command switch set to "laser lock" (Laser current decreases to zero)

    b. T4: Relay contact closes, shorting current to ground

The times T0-T4 refer to the times shown in figure 3.10. The control logic circuitry provides a very convenient method by which to safely power up and power down the bias current supplying the laser diode.

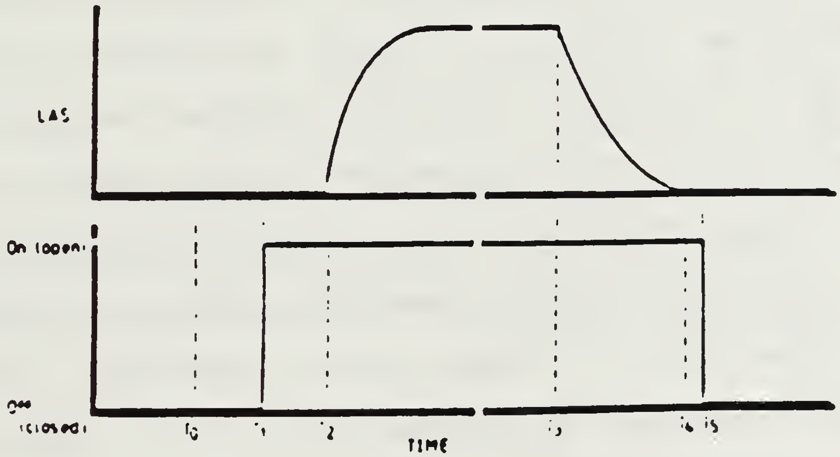

Figure 3.10. Switch On/Switch Off Sequences (from Ref. 11)

2. Circuit Results

The bias current supply circuit shown in Figure 3.7 produced an actual D.C. supply current range of between 4mA and 100mA. This result was obtained as the 2K ohm potentiometer was brought over its entire range producing a reference voltage at the input of the EL2020 over the range of 0V to 4V. Of course the actual current maximum is limited by the current limit potentiometer which provided a current limit range of 35mA to 125mA.

The low pass filter was constructed of a basic LC network using two capacitors and ten turns of 30 gauge wire around a ferrite core, 1.3 cm in diameter. This filter produced a half-power (-3 dB) cutoff frequency of 87 Hz. The slow start switch-on/switch-off control logic was tested for all possible conditions with very good results. Changing of the laser switch control from the 'Laser Free' to the "Laser Lock" position produced a subsequent decrease in voltage from 12 volts to 0 volts (24 seconds) on the emitter leg of the 2N498 transistor feeding the relay. The "Power Failure" signal produced the same results, as expected. Voltage readings on the drain of the 2N4360 FET feeding the bias supply circuit showed the FET to cut off under the "Laser Lock" or "Power Failure" condition. A slow decrease in voltage (24 seconds) from 7V to 0V was observed. This testing showed the correct operation of the slow start and stop of laser supply current in order to protect the laser from significant transients.

E. MODULATION CIRCUITRY

1. Description

In order to incorporate this drive unit into a useful communications system, the capability to modulate a signal and provide it to the laser diode is a necessity. The method used to accomplish this feature is shown in figure 3.11. This circuit is placed in parallel with the laser diode allowing the summing of the bias current and modulation current at a common node feeding the laser diode.

At the heart of the modulation circuit is an Elantec EL2020 current feedback amplifier, and an EL2004 FET line driver. These devices were chosen for use because of their characteristics shown in table 3-1. The 350 MHz unity gain bandwidth of the EL2004 yields a very good modulation capacity. The input to the EL2020 is the modulation data signal (via a 33uF A.C. coupling capacitor) at the non-inverting input, with a single output feeding the EL2004 line driver, providing an intensity modulated current to the summing junction to be applied to the laser diode. A 10uF capacitor is included for A.C. coupling to the laser diode.

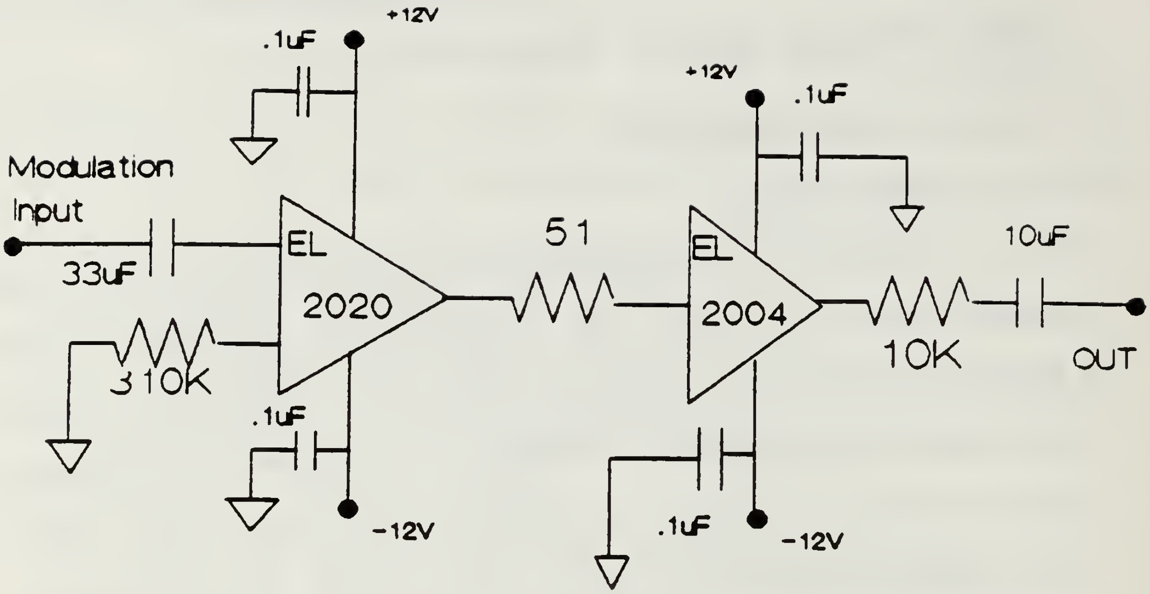

Figure 3.11. Source Modulation Circuit

TABLE 3-1
EL2020 & EL2004 CHARACTERISTICS

	EL2020		EL2004	
Slew Rate	500		2500	V/usec
Rise Time	25		1.0	nsec
Bandwidth (Unity Gain)	50		350	MHz
Supply Current	9		20	mA
Input Voltage Range	+\-5	to	+\-15	V
Max Output Current	33		100	mA
Input Impedance (Nominal)	$5x10^6$		10^{12}	Ohms
Output Impedance (Nominal)	5		6	Ohms

2. Circuit Results

The test signal provided to the input of the modulation circuit of figure 3.11 was a 10 volt amplitude sinusoid. Output current amplitude was +\-15mA over an operational test range of 1 Hz to 250 kHz and increased slightly beyond the 250 kHz (up to 50 MHz) to a peak of +\-20 mA. Therefore, the intensity modulation of the laser is frequency dependent. This must be accounted for when setting the bias current and current limit levels to allow for full swing of the modulation signal about the bias point, while remaining on the linear, lasing portion of the laser diode characteristic curve. The bandwidth of this circuit is limited in its present configuration by the 50 MHz bandwidth of the EL2020. The bandwidth of the EL2004 line driver is 350MHz. Therefore, to improve this specification, replacement of these components with ones of higher bandwidth ratings is necessary. Most modern laser diodes on the market today can be modulated at frequencies in the GHz range as discussed in chapter two.

F. LASER DESCRIPTION/UNIT INTERFACE

1. Description

The laser used in all testing of this drive unit is a Lasertron QLM-1300SM laser diode. This laser is a GaInAsP buried heterostructure laser incorporated into a 14 pin DIL package. Also incorporated into this package is a low current thermoelectric cooler, a precision thermistor and a high performance GaInAs monitor photodiode. A Corning single mode fiber is coupled to the laser using a taper and microlens coupling scheme to provide for minimal optical feedback and good coupling efficiency. Complete specifications for the laser are given in Table 3-2.

TABLE 3-2.
Lasertron QLM1300SM Specifications (from Ref. 7)

	MIN	TYP	MAX
Emmission Wavelength (nm)	1290	1310	1330
Spectral width (nm,FWHM)	--	--	4.4
Fiber Coupled Pwr @ Max I (mW)	1.0	1.2	1.4
Fiber Coupled Pwr @ I_{TH} (mW)	--	0.005	0.02
Threshold Current (mA)	--	49	55
Forward Voltage @ Rated Pwr (V)	1.2	1.4	1.8
Mon. Photocurrent@ Rated Pwr(uA)	50	100	500
Mon. Dark Current (uA)	--	0.1	0.25
Mon. Rise Time into 50 Ohms (ns)	--	--	1.0
Cooler Current @ 65 C (mA)	500	625	800
Cooler Voltage @ 65 C (V)	1.1	1.24	1.5
Cooler Response Time (sec)	--	30	--
Thermistor Resist 25 C (KOhms)	9.8	10.0	10.2
Thermistor Temp. Coef. (%/C)	--	-4.4	--
Operating Temperature Range (C)	-20	--	65

2. Feedback Circuits.

Figure 3.1 shows two feedback signals from the laser diode to the drive circuitry for positive and automatic (once settings are made) control of the laser diode output. The first of these signals is the optical power output of the laser being measured by the monitor photodiode mounted at the rear facet of the laser. This scheme allows for positive control of the optical power being launched into the optical fiber.

The second feedback signal is that of the thermistor, which is for the most part a resistance temperature detector which changes its resistance value in direct proportion to changes in the laser operating temperature. The resistance change is sensed by the thermistor detector circuit shown in figure 3.12 and an appropriate signal based on the setpoint temperature (10K potentiometer) is generated and sent to the TE cooler drive circuit shown in figure 3.13. The TE cooler drive circuit receives this signal as an input to the inverting input of the MC34004 op amp which feeds the base of the TIP125 darlington transistor current source. This configuration provides up to 600 mA to drive the TE cooler (actual drive current is based on the input received from the thermistor circuit). This scheme yields a closed loop system that maintains a stable laser diode operating temperature by providing more D.C. current to the cooler as laser temperature increases and less current as temperature decreases. Exact thermoelectric cooler specifications are included in Table 3-2 with laser diode specifications.

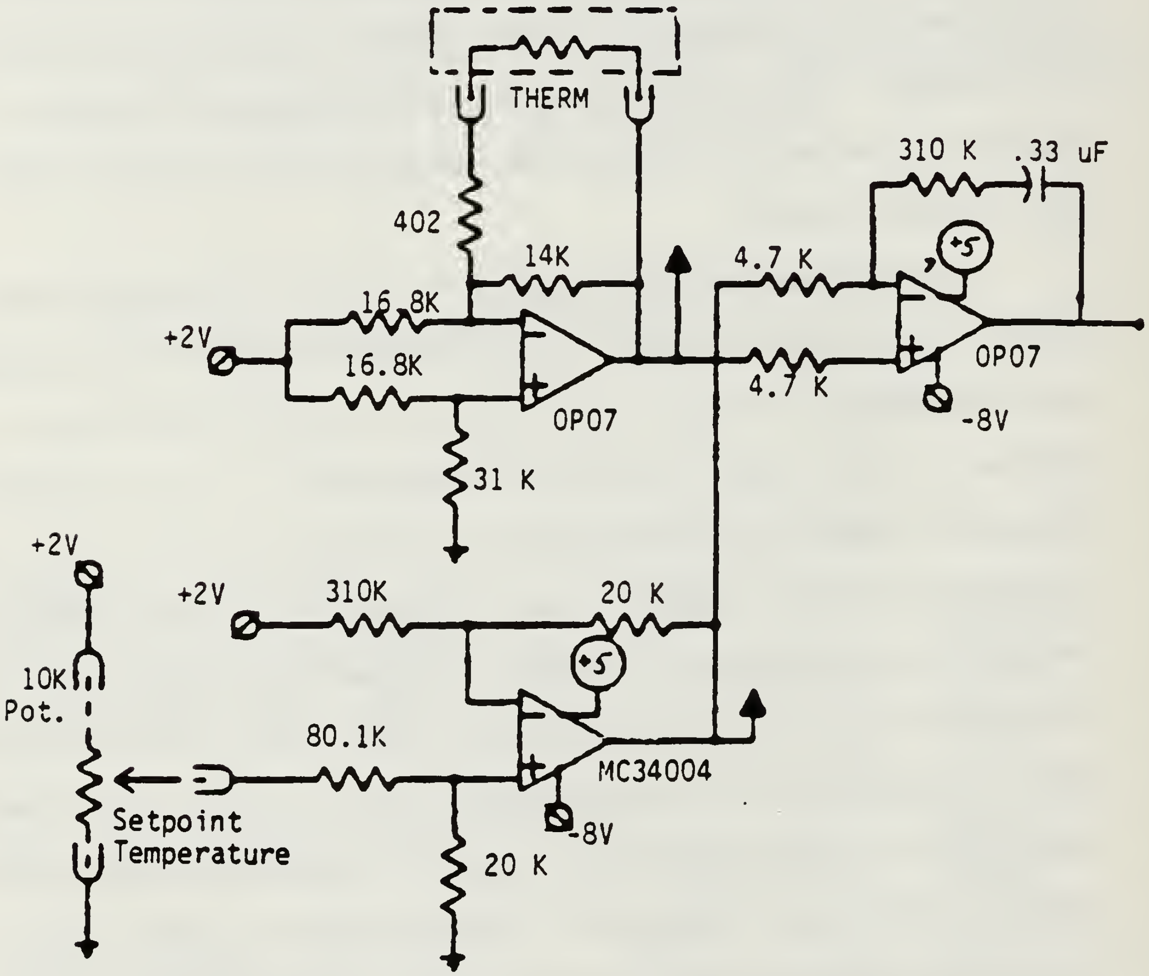

Figure 3.12. Thermistor Circuit (from Ref. 8)

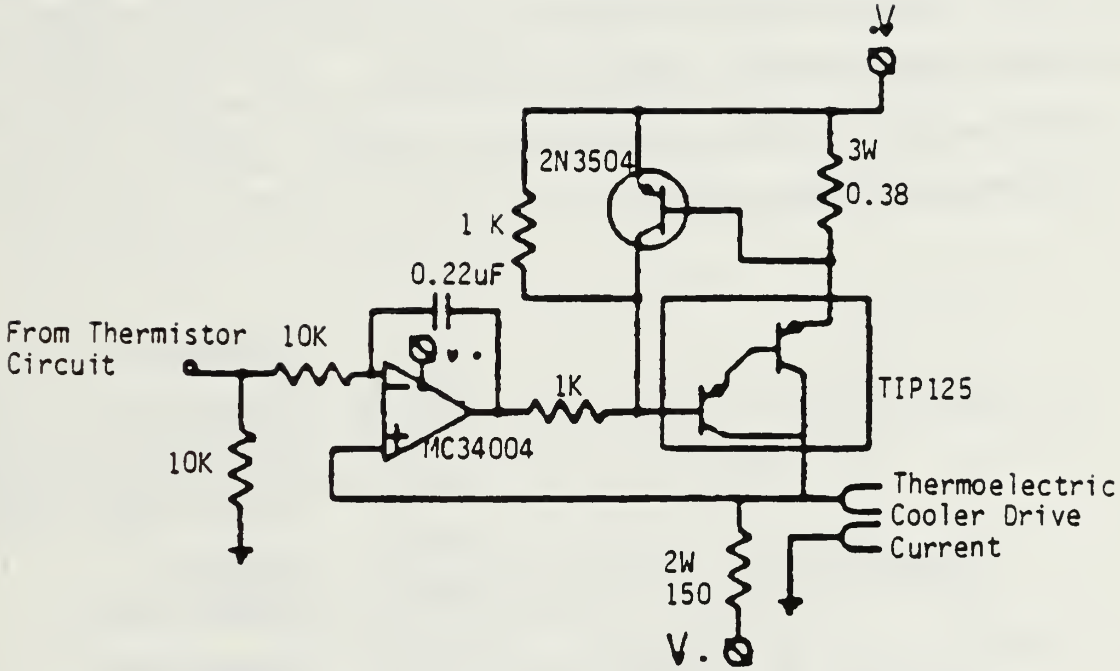

Figure 3.13. Thermoelectric Cooler Drive Circuit (from Ref. 8)

3. Laser Diode Interface with Driver.

The laser diode is incorporated into the drive circuit in parallel with the relay of the slow start control logic shown in Figure 3.9. As previously mentioned, this protects the laser from start up transients which could damage the laser. Figure 3.14 shows the pinout of the Lasertron laser. The DIL package utilizes 14 pins. Pin 5 should be connected to the unit casing ground for proper grounding of the laser. The laser package provides for the two different input signals (laser drive, TE cooler drive), and two different output signals (monitor photodiode optical power out, thermistor laser temperature).

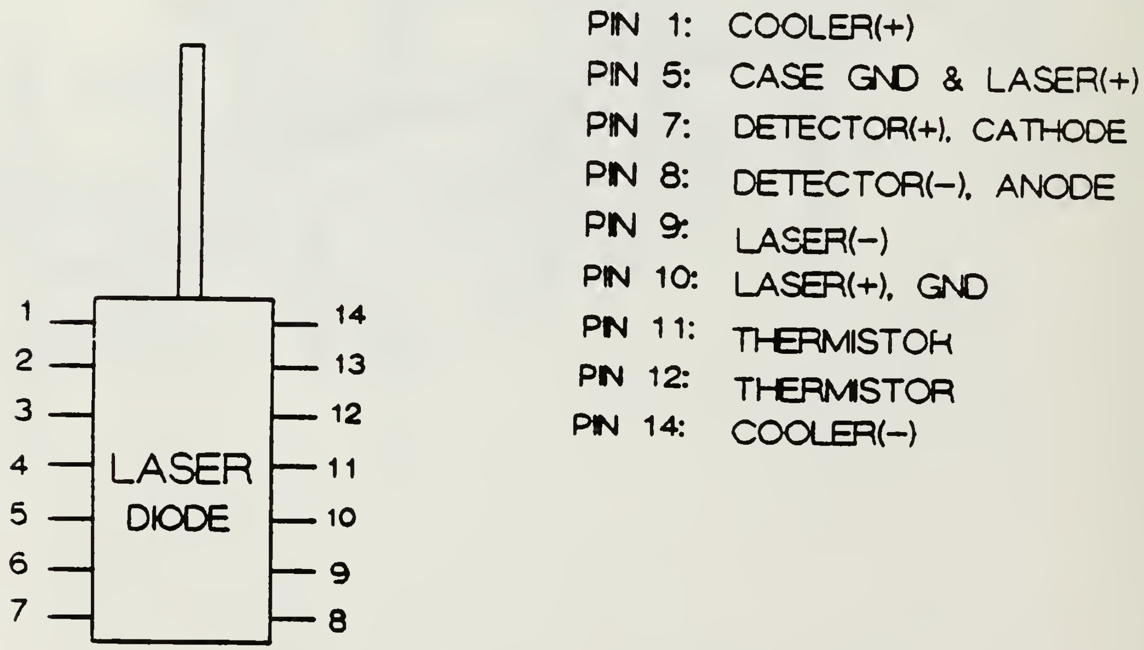

Figure 3.14. Lasertron Laser Diode Pinout (from Ref. 10)

IV. OPERATIONAL PROCEDURES

A. OPERATIONAL PRECAUTIONS

Operation of this semiconductor laser diode power supply and driver is quite elementary, provided a few precautions are observed and strict adherence to start-up and shutdown procedures are followed. These procedures should provide reliable and accurate operation of the laser diode. Carelessness may cause serious and permanant damage to the drive unit and/or the laser diode itself. Since long wavelength laser diodes similiar to the type used in this design work cost upwards of $2000.00 per unit, careless operation can become quite expensive.

B. UNIT SETUP

The following procedures should be followed prior to powering any laser diode with this unit:

1. Ensure bias current setpoint potentiometer is set to minimum (fully CCW)
2. Set current limit potentiometer to minimum (fully CCW)
3. Ensure lase switch control set to "Laser Lock"
4. Setpoint temperature set to desired laser operating temperature (Nominally 25 C)

* NOTE. Current limit operates on the sum of bias current and analog input current and will protect the laser diode if properly set prior to application of a signal to the laser diode.

Main power can now be applied to the unit by turning main power "ON". The switch provides the six volt D.C. power from the batteries to the power supply unit for conversion and regulation. Subsequent to main power "ON", the following procedures should be followed:

1. Set current limit setting for the specific laser diode being utilized

2. Set bias current to desired bias point of the laser (above threshold current for analog CW modulation)

3. Reverify setpoint temperature at desired temperature

When above parameters have been set, current to the laser diode can be applied by switching the laser switch control to the "Laser Free" position. This powers the relay which is shunting current to ground, and opens the contact. Power is now applied to the laser. The laser bias current can be changed manually by turning the bias control potentiometer. Specific knowledge of the laser threshold current is essential in setting an appropriate bias level for the particular application (i.e., CW modulation above threshold, ON/OFF keying both above and below threshold). As mentioned previously, sufficient bias must be applied for CW modulation such that the sum of bias and modulation current remains above threshold throughout the entire modulation cycle.

C. WAVELENGTH TUNING USING THE THERMOELECTRIC COOLER

As discussed in chapter two, the emission wavelength of laser diodes is a function of the operating temperature. This is due to the fact that the bandgap energy of a semiconductor decreases with increasing temperature. As a result, it can be seen from equation 2-1 that the wavelength of the laser output will increase as the bandgap decreases and the temperature increases. The resulting temperature coefficient for a typical laser diode is about 0.3 nm per degree celsius of temperature shift [Ref. 2:p. 227]. Utilizing this characteristic and knowledge of the emission wavelength of the laser at room temperature (25C), the laser can actually be tuned to a specific wavelength (within a reasonable range) by adjusting the laser operating temperature with the setpoint temperature control.

Changing the laser operating temperature directly affects the output wavelength in almost a linear fashion. This capability is probably most useful in a laboratory environment or application. However, using the knowledge of the relationship between laser temperature and emission wavelength, one could use the change in wavelength as a very expensive thermometer.

D. SHUTDOWN PROCEDURES

Unit shutdown procedures are for the most part a complete reverse of the startup sequence. The primary goal again, as in startup, is to avoid presenting current or power transients to the laser diode and to provide a smooth transition from lasing to non-lasing to off. As described earlier, this is accomplished quite well with the control logic portion of the laser drive circuit. Unit shutdown is as follows:

1. Set laser switch control to "Laser Lock" (this shuts the relay and shunts laser current to ground
2. Secure modulation input
3. Set bias current to Minimum
4. Turn Main power "Off"

E. SUMMARY

The above procedures are intended for use in a laboratory setup. The remote application discussed in the next chapter would obviously have application specific instructions for setup and subsequent automatic sequencing of startup and shutdown. This scenario most likely lends itself to microprocessor control as discussed in Chapter Six.

V. PROJECT APPLICATIONS

A. LABORATORY EQUIPMENT

The primary motivation for undertaking this particular thesis project was to develop a low cost laser diode driver capable of driving the available laser diodes presently being utilized for laboratory and research work at the Naval Postgraduate School. The driver being used at present is a Spectra Diode Labs (SDL) Model 800 CW laser driver which is a general purpose laboratory power supply and diode driver. This SDL driver meets all of the present needs and requirements of the Postgraduate School opto-electronics lab but at a cost of approximately $2000.00 per unit. The main goal then, was to develop a design that would also meet the needs of the lab and do so at a substantial monetary savings. The target cost for the completed unit was hundreds of dollars as opposed to thousands.

In the process of design development, it was decided to design the unit as a D.C. powered device capable of remote use. The unit varies in its applications as an educational tool in the lab environment. Actual presentation of the operational characteristics of a semiconductor laser diode can be demonstrated including the use of a bias point, optical feedback, modulation characteristics, and thermoelectric cooling including the wavelength tuning of the laser using the TE cooler as described in chapter four. The unit as constructed and detailed in chapter three would require no design modifications for use in a laboratory environment.

B. REMOTE LASER DIODE DRIVER

As stated in chapter one, this thesis is part of ongoing research at the Naval Postgraduate School involving long-haul underwater fiber optic communications links. In support of this research, the D.C. powered design of this drive unit could be adapted to serve as a drive unit subsystem for a semiconductor laser being used to transmit signals or data from an underwater sensor to a shore station for subsequent analysis.

In order to realize such an application, the unit must be capable of operating over a long period of time without battery replacement or maintenance requirements. Therefore, low power consumption is a must in order to make the drive unit practical for this application. Actual power consumption by the unit designed and constructed is 9.71 watts. This measured power is at a nominal operating point (bias current @ 50 mA, modulation current @ +\-15 mA sinusoid) and would obviously be slightly higher or lower depending on actual operating conditions.

Battery charges and/or replacement is not desirable in such a remote system. Thus, the use of CMOS (Complementary Metal Oxide Silicon) technology components in the design of the driver system is good engineering practice. The CMOS technology is very low cost, widely abundant, has a very wide non-critical power supply range, and uses no power when inputs are stable (not changing) and very little power when circuits are active (changing inputs). This results in a very low average power consumption by the CMOS components. One other very important characteristic of CMOS components is that they are capable of absorbing system noise and generate extremely low noise levels during output changes themselves. This is very important in an electro-optic communications system as the contribution of electronic noise to the system noise performance as a whole is minimized.

Since this unit would be deployed as part of an entire sensor and transmission system in an underwater environment, system reliability would be of primary design importance. Just as battery replacement in the remote unit is undesirable, component or entire sub-unit replacement due to failure is just as undesirable. The CMOS technology meets the reliability criteria very well as it is a mature technology (although still evolving to higher performance standards) with many designs and experience behind the technology base. As any design engineer would agree, system reliability is only as good as the least reliable subsystem or component. For this reason, the transmission system is critical to the operation of the communications link. The safety features and feedback mechanisms (for protection and control) in this design along with quality components yield a closed loop control system which is very reliable and self contained which is ideal for the remote application. Of course, an underwater system would also have to be designed to ensure watertight integrity of the system.

Interfacing a remote sensor with this unit would be quite easy as once a particular parameter or data was measured or detected, it would be provided to the modulation input of the laser driver (after appropriate signal conditioning) as shown in the schematic of Figure 3.11. This signal would then provide for the intensity modulation of the laser about the bias point and subsequent transmission via the fiber optic link. A system block diagram of a simple configuration is shown in Figure 5.1.

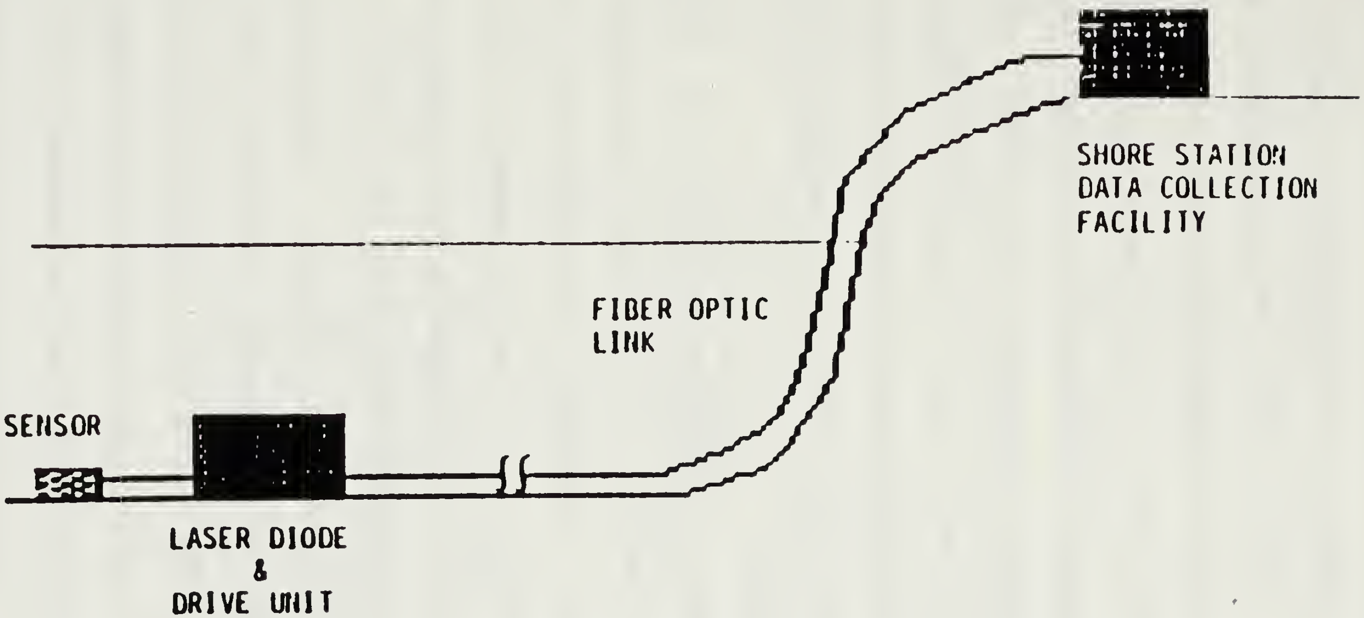

Figure 5.1. Block Diagram of Possible Remote System Application

VI. SUMMARY AND RECOMMENDATIONS

The primary objective of developing a low cost laser diode driver was achieved with good operational results. One of the main design problems throughout the course of the project was ensuring that all loads were able to be supplied with sufficient power. Development of the D.C. power supply turned into an iterative process. The overall current load is quite significant even with the use of low power components. This is only a problem for the remote applications discussed in Chapter Five, where the longest possible battery life is essential.

As mentioned, the design of this unit yielded very good operational results, and met the requirements as originally set forth. However, during the design, construction and testing phases, numerous improvements and added capabilities of the unit were considered. Among these improvements was the capability to place the control and display unit under microprocessor control. This particular feature is available on the Spectra Diode Labs (SDL) model 800 semiconductor laser diode power supply and driver. Figure 6.1 shows a basic block diagram of how the microprocessor could be incorporated into the present design in order to implement this automatic control and display. In effect, the microprocessor replaces the DIP switches presently being used to select the input to the DVM for subsequent display of the selected parameter.

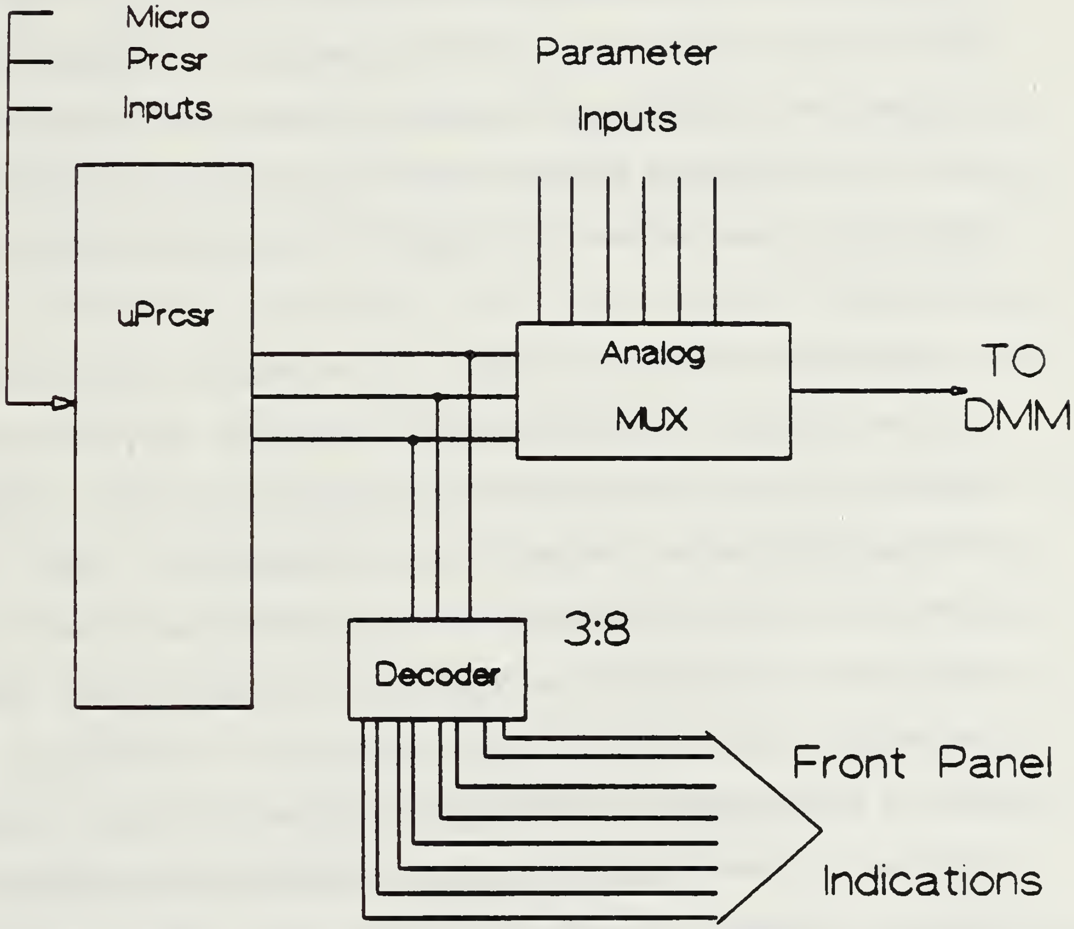

Figure 6.1. Microprocessor Controlled Unit

Another possible improvement to the design would be to increase the modulation bandwidth of the unit. As presently configured, the modulation bandwidth is 50 MHz. The primary limiting components are the current feedback amplifier (Elantec EL2020) and the FET buffer/line driver (EL2004) shown in the modulating circuit of figure 3.11. By replacing these two components with components of higher bandwidth ratings the modulation bandwidth capacity of the entire unit could be increased significantly as state of the art semiconductor laser diodes are capable of modulation in the gigahertz range.

As was stated previously, this thesis primarily covered baseband analog intensity modulation with very little discussion of other techniques. For analog baseband signals of greater bandwidths, Pulse Position Modulation (PPM) could be considered. By adding the flexibility of being able to choose between modulation schemes, a more optimal system (bandwidth x distance) can be realized. For example, by using a PPM format, a significant signal to noise ratio improvement over baseband analog intensity modulation would result. However, because of the narrow pulses characteristic of PPM, this format requires a bandwidth expansion of the baseband signal which is dependent on the exact SNR requirements of the system. Pulse Code Modulation (PCM) represents another alternative. This format also requires an increase in channel bandwidth over baseband, but generally not as great as that for PPM.

Future improvements to this design may include the capability for digital modulation techniques. On/off keying of the optical source is the most straightforward scheme to implement. In the digital system, Bit Error Rate (BER) replaces SNR as the measure of system performance. The noise performance of the digital system will in general be significantly better than that of the analog system. Digital systems employing ON/OFF keying can tolerate more harmonic distortion and exploit the advantages of the semiconductor laser diode. In the analog intensity modulated driver, nonlinear distortion components are produced by the source. The major alterations that would need to be made to the present design would be a change in the operating point of the laser to just below threshold to create a non-lasing output representing the OFF state. The bias point should be set as close to threshold as possible (but not on or over) in order to minimize the laser rise time. Figure 6.2 shows this operating condition on a plot of optical power vs. forward current. For any binary digital (pulsed) modulation technique (PPM, ON/OFF keying,etc.), the use of an FET as a current source switch (large bandwidth), is essential for optimum speed of response.

The data rate/bandwidth requirements of a digital system pushing the driver circuitry to its operational limits requires the entire transmission process to be A.C. coupled. These requirements dictate the need for careful consideration of pulse code formats, to provide two level unipolar pulses with no DC components in the binary encoded stream.

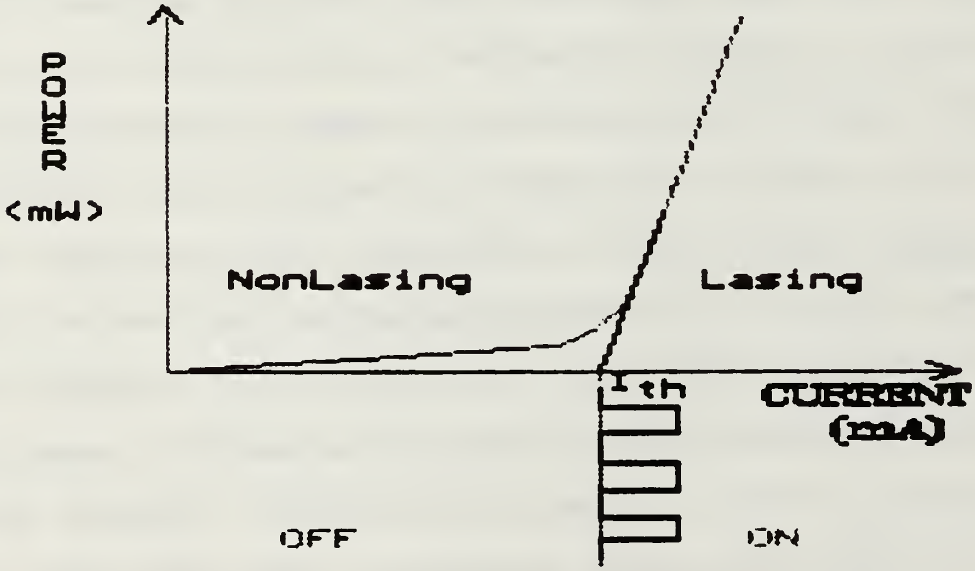

Figure 6.2. ON/OFF Modulation Operating Point

APPENDIX

THERMOELECTRIC COOLER SYSTEM DESIGN PROCEDURES

This appendix describes the procedure to be used in determining the current and voltage levels required for a specific application of thermoelectric coolers. The curves shown below are used only as an example and are taken from a specific type of TE module from a particular manufacturer.

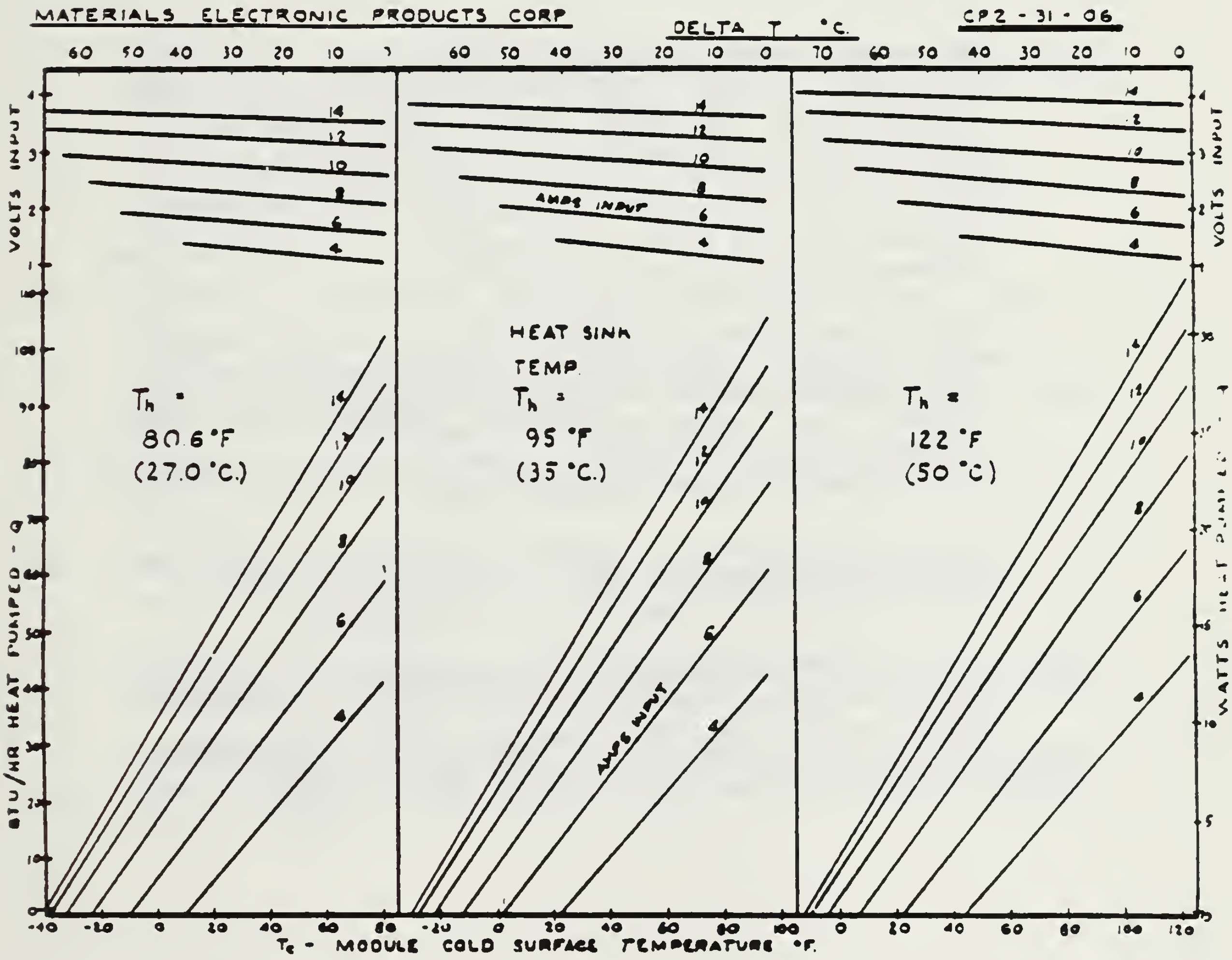

Figure A.1. Thermoelectric Cooler Design Curves (from Ref. 5)

Figure A.1 shows the graphs to be used in design of an appropriate thermoelectric cooler for any application that such technology can be applied. In the application of laser diode cooling, concern is with the primary heat source, the laser itself, however, the heat produced by support circuitry (radiant heat) must be accounted for. The use of these curves are as follows:

1. Determine available current in amps.
2. Determine Q, the total heat energy load that is generated by the entire unit (in BTU/HR or Watts).
3. Determine heat sink temperature and cold surface temperature (T_h and T_c) in ^oF.
4. Using the graph corresponding to the T_h temperature chosen, find the T_c temperature on the X-axis and go up to the line corresponding to the current available and look across to the Y-axis to determine the amount of heat that can be pumped by the TE module being used.
5. If the heat load is larger than the capacity of the module with the given conditions, then a second or third module may be required.
6. The input voltage can be determined by locating the T_c value on the X-axis and going up the chart to the available current line and reading off the value on the Y-axis for voltage.

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Semiconductor laser diodes and the design of a D.C. powered laser diode drive unit.

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